Basis for Interim Values for Lakes and Reservoirs

WQCD PREHEARING STATEMENT – EXHIBIT 13

12/9/2011

Table of Contents

1. Introduction

More than eight decades of scientific investigations show that adding nutrients to a lake increases the abundance of algae. Enrichment of nutrient supplies occurs almost entirely as the result of human population growth and associated land use changes. The process of human-caused enrichment is called "cultural eutrophication", and it is a serious threat to water quality.

Eutrophication has adverse consequences for water quality, which can impair beneficial uses, and for the value of the resource – Colorado's lakes – as a recreational amenity. Those consequences are the result of excessive abundance of algae, which increases the likelihood of water quality impairment and diminishes recreational value. However, setting a precise threshold for what constitutes "excessive" abundance is a challenging task.

Nutrients are unusual pollutants because they are not toxic to aquatic organisms[1]. Nutrients can *enable* algal growth by establishing an upper bound for algal abundance, but they cannot *compel* the algal community to reach that potential. Physical, chemical, and biological factors – including settling, mortality due to toxics, or consumption by grazing zooplankton – can reduce algal abundance, keeping it below the nutrient-driven potential at least some of the time. These factors introduce variability that can obscure the linkage to nutrients and complicate criteria[2] development.

The conceptual basis and technical development of nutrient criteria for Colorado lakes are presented in a series of sections in this document. "*Eutrophication: Process and Problem*" briefly describes the problem that is caused by nutrient enrichment and that is addressed by development of nutrient criteria. The criteria are intended to provide protection for uses in Colorado lakes, which are characterized in "*Description and Classification of Colorado Lakes*". Classifying lakes is a means of optimizing protection within the existing framework of uses.

The non-toxic nature of nutrients and chlorophyll makes it possible to consider a range of policy options for criteria development. In contrast to toxic pollutants for which regulatory protocols for deriving criteria are well-developed (tests for acute and chronic thresholds), nutrients may be amenable to a more flexible approach. "*Policy and the Approach to Nutrient Criteria Development*" describes the reasoning behind the aim of striking a balance in developing nutrient criteria for lakes. The focal point for criteria development is the aquatic life use. As a practical point of departure, a healthy, productive fishery is taken as evidence of support for the aquatic life use. Then, potential conflicts with recreational or aesthetic interests are evaluated. For example, the chlorophyll concentrations that support a productive fishery may be too high to satisfy an aesthetic interest in water clarity. As long as

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[1] Nutrients are not toxic at the concentrations generally considered relevant for nutrient criteria, except possibly ammonia. Those nutrients considered toxic at higher concentrations are regulated by separate criteria based on toxicity rather than capacity to support algal abundance.

[2] In this document, the word *criteria* (sing. *criterion*) is used to indicate a numeric value (magnitude) for which frequency and duration components also have been, or will be, defined. It is a formal threshold that could be adopted as a water quality standard. Criteria developed in this technical document appear as "interim numeric values" in Section 31.17 in the hearing notice.

related water quality criteria – such as pH and dissolved oxygen – are met, tradeoffs between fishery yield and water clarity present a range of viable policy options for developing nutrient criteria.

The primary measure of a lake's response to nutrients is the level of algal abundance, which is measured as chlorophyll concentration. "*Characterizing Algal Abundance*" characterizes seasonal and inter-annual patterns of algal abundance within and among lakes. Algae are short-lived, rapidly growing organisms, whose abundance can change very quickly. As a result, the variability observed in chlorophyll concentrations is often greater than what is observed for most conservative substances (e.g., calcium or chloride). Consequently, understanding and describing the variability in algal abundance is an important part of nutrient criteria development. In particular, the analysis establishes the basis for the duration component of the criteria and provides the relationships used to develop the frequency component.

The capacity of a lake to support algae is determined largely by the nutrient supply – a greater supply of nutrients generally means that algae are more abundant. The relationships between nutrients and algal abundance are explored in "*Nutrients and Algal Abundance*". Special attention is given to the role of nitrogen. The quantitative relationships are used to translate acceptable levels of algal abundance into allowable concentrations of nutrients (i.e., the magnitude component of the criteria).

Algae are responsible, directly or indirectly, for most of the water quality impacts associated with nutrient enrichment of lakes. When algae become abundant, water quality impacts are more likely to occur. These impacts are described in "*Algal Abundance and Water Quality Impacts*." Some of the impacts, like elevated pH or depletion of dissolved oxygen, are subject to assessment with separate criteria, but others are not. For example, the occurrence of algal blooms and the production of algal toxins are not presently covered by separate criteria, but these aspects of water quality can still be helpful for shaping policy recommendations regarding the magnitude component of the proposed criteria.

The Division is casting criteria recommendations in terms of trophic condition, which is a concept widely used to describe lake productivity. "*Defining Trophic Condition*", develops chlorophyll and nutrient criteria consistent with long-term maintenance of a target trophic condition that is defined separately for Cold and Warm lakes in Colorado. The target trophic condition unites the different criteria elements (algal abundance and nutrients) in a common biological framework that facilitates evaluation of water quality implications at different time scales. This is the stage of the analysis where it becomes possible to evaluate the need for, and magnitude of, tradeoffs intended for balancing interests.

The Division has relied primarily on data from Colorado lakes for the technical development of nutrient criteria. Inevitably, questions will arise about the adequacy of sample size and the confidence in conclusions reached. A useful way to address those concerns is to introduce a broader perspective by comparing the Division's proposed criteria to those proposed or adopted by other states. The studies undertaken by other states and the conclusions they have reached provide an opportunity for comparing criteria developed independently, but with similar intent. The context is valuable because it broadens scientific and policy perspectives beyond the political boundaries of each state. These comparisons are presented in "

Context for Criteria Development ". An "apples-to-apples" comparison is made by restricting attention to criteria applicable to similar fishery types, and by making adjustments to duration and frequency so that there is a common basis for comparing magnitudes.

2. Eutrophication: Process and Problem

Lakes vary considerably in terms of the algal abundance they support. To a large extent, algal abundance is determined by the supply of nutrients; lakes with higher nutrient levels generally support a greater abundance of algae. Although lakes form a continuum of algal abundance, researchers have found it useful to aggregate lakes into categories called trophic states.

Lakes with low algal abundance are called oligotrophic, those with moderate algal abundance are called mesotrophic, and those with high algal abundance are called eutrophic. There is also a category (hyper-eutrophic, or sometimes hypertrophic) for lakes with extremely high algal abundance. Trophic states are descriptive and can enable broad generalizations about water quality and use support (Table 1).

Trophic State	General Characteristics	Water Supply	Fishery & Recreation
Oligotrophic	High clarity; dissolved oxygen always present in hypolimnion	May not require filtration	Salmonids
Mesotrophic	Moderately clear; hypolimnion may be anoxic	Requires filtration Mn, Fe, taste&odor problems possible	Walleye
Eutrophic	Algal scums increasingly likely; hypolimnion anoxic	As above, but more significant	Warm-water fisheries (bass)
Hyper-eutrophic	Dense algal growth forming scums; strong likelihood that Cyanobacteria will dominate phytoplankton community	As above, but more significant; potential concern about cyano-toxins	Rough fish dominate; Swimming and boating may be undesirable due to algal abundance

Table 1. Qualitative characterization of lake trophic states. Descriptions adapted in part from Carlson's work; see website: http://dipin.kent.edu/tsi.htm

The general characteristics of trophic states can be captured in narrative form, but there are classification systems that use fixed boundaries to partition the trophic continuum into several trophic states. Chlorophyll concentration, which is a common measure of algal abundance, is the primary metric for determining trophic state. Nutrient concentrations and transparency (Secchi depth) are also used to delineate boundaries, although they are not typically the primary determinants.

Four fixed-boundary classification systems are compared in Table 2. The Organisation for Economic Co-operation and Development (OECD 1982) and Carlson[3] (Carlson 1977) systems are familiar to most limnologists, but the Burns system (Burns et al. 1999) is not. The National Lake Assessment (NLA) classification[4] is quite new, having been developed as part of the recent EPA assessment. Although they may differ in terms of the numeric values used as boundaries, each could serve as a qualitative basis for conveying information about water quality expectations.

[3] http://dipin.kent.edu/tsi.htm
[4] http://www.epa.gov/owow/lakes/lakessurvey/pdf/nla_chapter5.pdf

Category	Source	Mean Chl, ug/L	Max Chl, ug/L	TP, mg/L	TN, mg/L[5]	Secchi, m
Ultra-Oligotrophic	OECD	1.0	2.5	0.004		12
	Carlson[6]	0.95		0.006	0.184	8
	Burns[7]	0.82		0.004	0.073	15
Oligotrophic	OECD	2.5	8.0	0.010		6
	Carlson[8]	2.6		0.012	0.367	4
	Burns	2.0		0.009	0.157	7
	NLA	2.0				
Mesotrophic	OECD	8.0	25.0	0.035		3
	Carlson	7.3		0.024	0.735	2
	Burns	5.0		0.020	0.337	2.8
	NLA	7.0				
Eutrophic	OECD	25.0	75.0	0.100		1.5
	Carlson[9]	56.0		0.096	2.938	0.5
	Burns[10]	31.0		0.096	1.558	0.4
	NLA	30.0				
Hyper-eutrophic	OECD	>25	>75	>0.100		<1.5
	Carlson	>56		>0.096	>2.938	<0.5
	Burns	>31		>0.096	>1.558	<0.4
	NLA	>30				

Table 2. Fixed boundary classification of trophic state with water quality variables.

The Process of Eutrophication

In the absence of significant trends in nutrient supplies, the trophic state of a lake and the abundance of algae in that lake should remain stable. The stable state is considered *trophic equilibrium*[11] and it represents the long-term response of a lake to its nutrient supplies. The equilibrium concept does not mean that chlorophyll and nutrients are constant; variability around the long-term response is expected from year-to-year.

Trophic state can be expected to change in response to a significant trend in nutrient supplies. *Eutrophication*[12] is the term applied when trophic state is changed (e.g., to eutrophic from mesotrophic) by a significant increase in nutrient supplies. *Oligotrophication* is sometimes used to describe the change in trophic state that occurs in response to a significant decrease in nutrient supplies.

[5] Total nitrogen (TN) values for the Carlson index were derived from Kratzer and Brezonik (1981), who developed an equation based on the methodology of Carlson.
[6] Trophic State Index (TSI)<30
[7] Includes "microtrophic" and "ultra-microtrophic"
[8] TSI 30-40
[9] TSI 50-70
[10] Includes "eutrophic" and "supertrophic"
[11] Edmondson (1991) developed the concept of trophic equilibrium and applied it toLake Washington.
[12] In this document, eutrophication is based solely on algal abundance and does not include the long-term aging process of natural lakes that is also referred to as eutrophication by some, but not all, experts. [See Edmondson (1991) for insightful commentary on the subject.]

Typically, nutrient increases are the result of human actions, making the term "cultural eutrophication" more accurate. Concern about increases in algal abundance and the associated water quality implications creates incentive to forecast the changes expected when an increase in nutrients is anticipated, or when restoration is required.

Predictions of the outcome of eutrophication, or its reversal, are typically made using empirical relationships between chlorophyll and nutrients (see *Nutrients and Algal Abundance* for more details). There are many examples in the literature of these relationships, and all are based on data drawn from many lakes. One widely cited example is the Jones-Bachmann relationship that plots chlorophyll as a function of total phosphorus concentration (Figure 1).

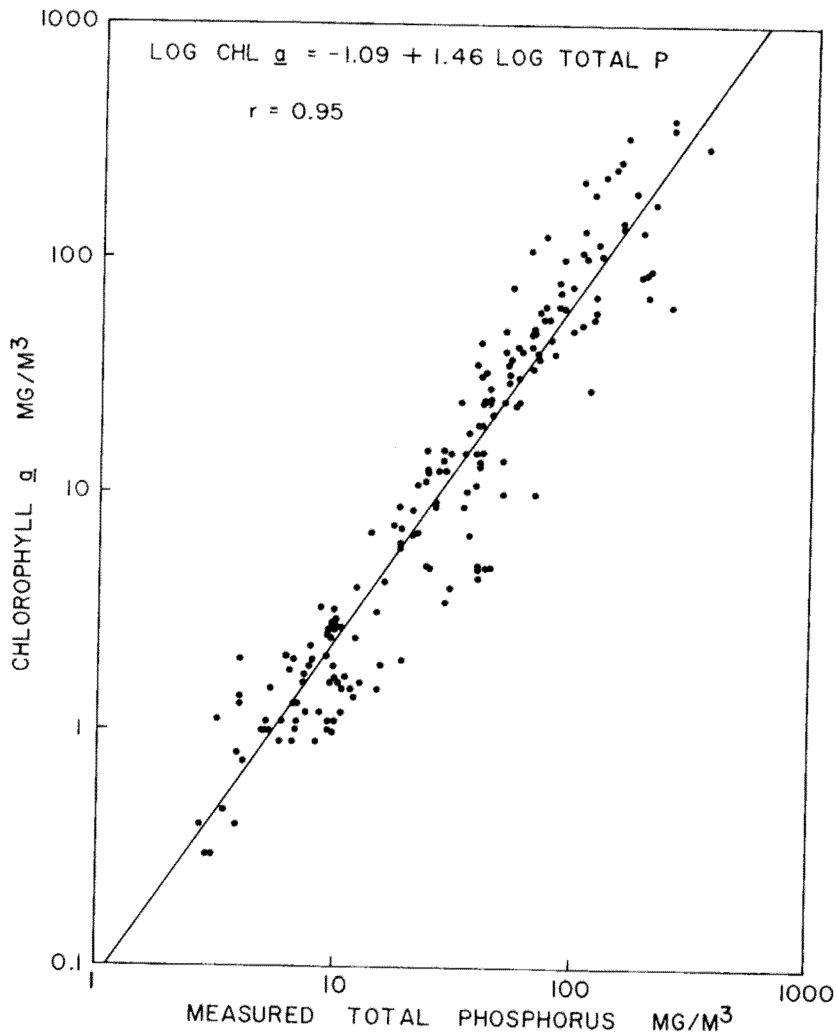

Figure 1. Relationship between chlorophyll and total phosphorus in 143 lakes in the U.S. (from Jones and Bachmann 1976).

Empirical relationships between chlorophyll and nutrients typically are based on data from many lakes, providing a range of concentrations spanning the trophic continuum. These relationships provide guidance for expectations in a lake where there is a trend in nutrient loads. However, they are not intended for predicting year-to-year variability in a lake with stable trophic conditions (cf. Reynolds 2006).

The Problem of Eutrophication

The capacity of eutrophication to produce serious water quality problems has been recognized for many years. It has been studied thoroughly with respect to causes and consequences, and it is routinely featured in textbooks of limnology (e.g., Wetzel 2001) and environmental engineering (e.g., Masters and Ela 2008). Increasing nutrient supplies increases the abundance of algae, leading to a long list of potential water quality problems including elevated pH, reduced clarity, depleted oxygen, cyanotoxin formation, taste-and-odor problems, formation of disinfection by-product (DBP) precursors, and shifts in fish community composition. The water quality problems that arise from eutrophication are the result of the ordinary biological processes performed by algae present at excessive levels of abundance.

Evidence for eutrophication and the consequences of excessive algal abundance is available for Colorado lakes. Four lakes – Barr, Milton, Horse Creek, and Prospect – are on the 303(d) list due to elevated pH, which is the result of excessive algal abundance. Milton and Prospect also are on the 303(d) for low dissolved oxygen, and Barr and Horse Creek are on the Monitoring & Evaluation list for low dissolved oxygen. Other Colorado lakes, including several Denver urban lakes, are listed for low dissolved oxygen[13]. These problems are the result of excessive algal abundance.

In addition, the sheer abundance of algae during a "bloom" event can have a very detrimental effect on the recreational experience, either from direct contact, or from the aesthetic perspective. Little information is available for some of the other, as yet unregulated, water quality problems associated with eutrophication, such as the production of geosmin[14], which causes taste-and-odor problems in drinking water.

The water quality problems caused by eutrophication also impose costs because they affect the value or quality of particular uses. When eutrophication diminishes water quality in a drinking water reservoir, for example, it may cost more to make that water potable. Lakefront property values and recreational use may suffer the "greatest economic losses" due to eutrophication, according to a recent study (Dodds et al. 2009). Other costs may be more difficult to assess – such as non-use or option values[15] – but the tools exist. A conceptual framework summarizing the many pathways by which eutrophication could affect the value of "ecosystem goods and services," including recreation is shown in Figure 2.

[13] Recent changes in assessment methodology for dissolved oxygen will affect the number of lakes on the list.
[14] Geosmin is a chemical produced by some blue-green algae (Cyanobacteria). It imparts a distinctive and unpleasant taste and smell to drinking water that elicits complaints from customers.
[15] Terminology from Kramer (2005)

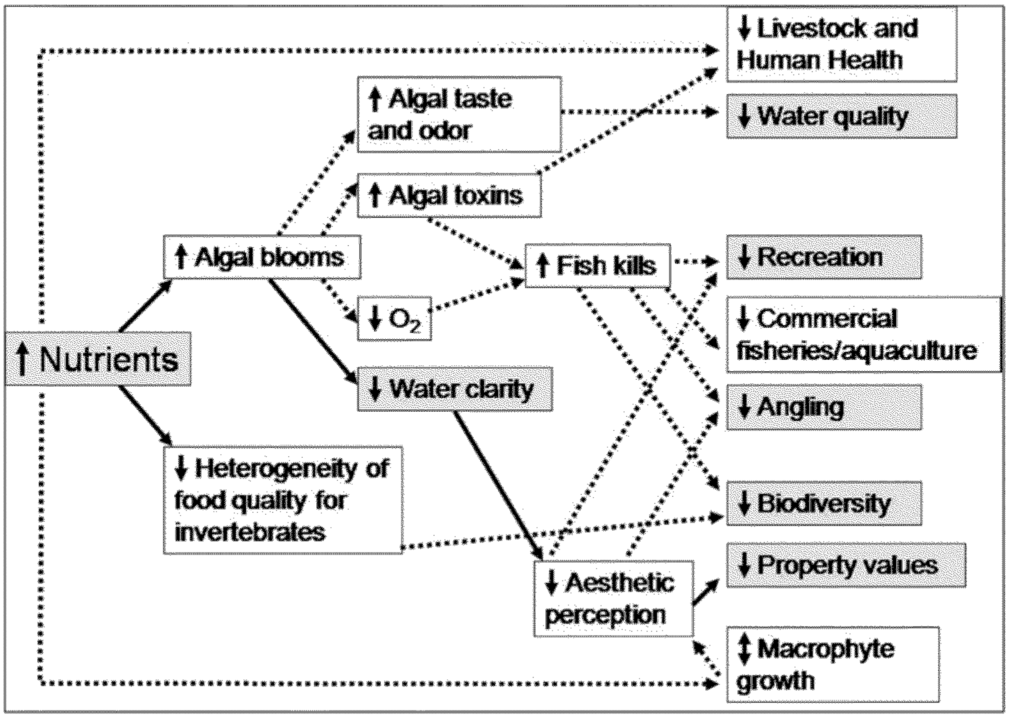

Figure 2. Pathways by which high nutrient concentrations may affect ecosystem goods and services. Copied from Dodds et al (2009).

To the extent that eutrophication has been allowed to proceed to date, a cost has already been incurred. If nothing is done to curtail or reverse current trends for increasing nutrient supplies, the costs can be expected to increase as a result of increasing population. The population of Colorado is expected to increase by about one million over the next decade[16]. Assuming the additional people would be connected to sewer systems, the expected increase in nutrient loads from point sources alone would be about 20 percent.

Concern about eutrophication is not new, or even new to Colorado. Studies performed during the early 1980s as part of the national Clean Lakes Program provided motivation for the WQCC to adopt site-specific standards and associated reservoir control regulations intended to avert eutrophication or to reverse its effects (Table 3). Pro-active implementation of control measures has been largely successful in preventing the increases in nutrient loads that had been anticipated with increasing development in each of the basins. In addition, concern about the effect of eutrophication led to the adoption of a site-specific narrative standard, based on trophic state, for a water supply reservoir (Standley Lake).

Lake	Total Phosphorus, mg/L	Chlorophyll, ug/L	Adopted	Comment
Bear Creek	Narrative		1992	Intended to reverse eutrophication and return trophic state to the boundary

[16] State Demography Office forecasts, accessed 10/11/2010, for 2020 compared to 2010 on website: http://dola.colorado.gov/dlg/demog/pop_colo_forecasts.html

Lake	Total Phosphorus, mg/L	Chlorophyll, ug/L	Adopted	Comment
				between mesotrophic and eutrophic
Bear Creek	0.032	10	2009	Acknowledges that internal loading, which is a legacy effect of historical eutrophication, will delay prospects for attainment
Chatfield	0.027	17*	1984	Hold as close to historical trophic state as possible
Chatfield	0.030	10	2009	Reaffirms commitment to preserve historical trophic state, and adjusts standard to better reflect those conditions
Cherry Creek	0.035	15*	1984	Hold as close to historical trophic state as possible
Cherry Creek	0.040*	15	2000	Adjusts standard to better reflect target conditions
Cherry Creek		18	2009	Adjusts standard to better reflect target conditions
Dillon	0.0074		1984	Preserve 1982 trophic state
Standley	Narrative		1994	Maintain as mesotrophic
Standley		4.0	2009	Concern about drinking water quality

Table 3. History of site-specific nutrient criteria development and implementation in Colorado reservoirs. Most of the numeric criteria were adopted as standards, but a few (marked by asterisks) are goals. Reservoir Control Regulations also have been adopted for all except Standley Lake.

Colorado's experience with site-specific nutrient standards has shown that regulating nutrients can prevent the eutrophication normally anticipated as a consequence of development. The effort expended on development of the initial criteria and subsequent modifications to those criteria have provided the Division with experience useful for developing criteria for lakes throughout the state. In particular, experience has revealed some of the difficulties of conducting assessments solely on the basis of narrative criteria and has shown the need to add chlorophyll criteria. Both lessons have been valuable in the present effort to develop nutrient criteria for lakes. The Division also has learned, on the basis of experience with Bear Creek Reservoir, that reversing eutrophication can be an extremely slow process when the legacy of historical eutrophication includes internal phosphorus release.

Efforts to reverse eutrophication have been studied in many lakes, chiefly in Europe and the US. Some, but not all, efforts have been spectacularly successful (e.g., Lake Washington). The chief impediment to restoration seems to be internal nutrient loading (chiefly phosphorus), which may persist for decades after external nutrient loads have been reduced significantly (Jeppesen et al. 2005). Uncertainty about prospects for successful reversal of eutrophication argues persuasively for emphasis on prevention wherever possible.

3. Description and Classification of Colorado Lakes

Colorado has many water bodies that are considered "lakes" in a broad sense. A recent count based on the National Hydrography Dataset (NHD), puts the number in excess of 7000.[17] The count includes lakes of all sizes, elevations, and origins. On maps, they might be labeled as lakes, ponds, or reservoirs. These terms lack formal definitions, although common usage of "pond" generally conveys the idea of a small water body, and "reservoir" always means a man-made water body. All three terms appear in basin regulations, albeit without accompanying definitions. No attempt is made here to clarify the terminology. Instead, the practice in this document is to use the term "lake" in the broadest sense to apply to ponds and reservoirs as well as natural lakes.

Basis for Classification

Classification creates the framework for developing criteria by grouping lakes with similar expectations for nutrient-related water quality conditions. Expectations could be the result of having defined reference conditions, or they could be derived to protect a specific use or interest. In either case, classification may take into account important attributes of a lake or its watershed.

Differences among lakes can be discerned for a variety of factors including physical characteristics – such as surface area, depth, or elevation – and man-made vs. natural origin. For those differences to be useful, however, they should improve the basis for protecting uses, and there must be enough lakes in each category to support development of criteria.

Surface Area

Most lakes in Colorado are small and at high elevation. About 60 percent of the "lake objects" identified in the NHD were smaller than 10 acres, which was the lower size limit for inclusion in the recent National Lake Assessment (NLA). Many of these small lakes are in the sub-alpine zone (Nelson 1970) and are not readily accessible for sampling. They have not been part of the Division's routine monitoring program[18], and they also were excluded from the NLA sampling program.

Surface area provides a basis for dividing Colorado lakes into two categories, but, unfortunately, this classification is driven more by the shortage of data with which to test for differences rather than a demonstration of differences that can improve the basis for regulation. Nevertheless, Colorado is not alone in excluding small lakes from application of numeric criteria, as discussed later.

Elevation

Colorado has lakes at all elevations, and elevation translates into a strong environmental gradient for temperature. The role of temperature in shaping aquatic communities is acknowledged in Colorado's existing classification scheme that divides lakes into two Aquatic Life Use categories – Cold and Warm.

[17] The number of "lake objects" detected in Colorado when EPA was developing the list of candidate sites for the National Lake Assessment (NLA). The counts, partitioned by lake area, were made available by Tony Olsen of USEPA NHEERL, Corvallis, OR. Not all lake objects were eligible for sampling in the NLA. Some were excluded on the basis of size (<10 acres), and others were excluded because they were intermittent or served a special purpose (e.g., sewage treatment).

[18] Plans have been developed for sampling small lakes at high elevation and a preliminary survey was conducted in 2011, but it will be years before a comprehensive data set is available for analysis.

The two categories are separated by determining whether the aquatic biota is "normally found in waters where the summer weekly average temperature…frequently" is below or above 20°C.

The strong linkage between temperature and elevation means that high elevation lakes are classified as Cold and low elevation lakes are classified as Warm. There is no "bright line" marking the boundary between Cold and Warm lakes, but in simplistic terms, Cold lakes are expected to support trout populations and Warm lakes are not.

Generalizations about environmental differences between Cold and Warm lakes are summarized in Table 4. Colder air temperatures at high elevation mean lower water column temperatures in summer and persistent ice cover in winter. High elevation lakes also tend to have lower solute concentrations because of the geologic setting for the watersheds and the relatively brief time (distance from headwaters) for weathering to release solutes. Lower concentrations of solutes, including nutrients, generally mean that Cold lakes are less productive and more transparent than Warm lakes. In addition, for larger lakes, those at higher elevation tend to be deeper and thus more likely to stratify persistently during the summer.

Attribute	Cold	Warm	Comment
Elevation	Most above 7000 ft	Most below 5000 ft	Strong environmental gradient affecting temperature and total dissolved solids (TDS)
Summer Temperature	Colder	Warmer	By definition
Ice cover	Persistent	Brief or intermittent	
Depth	Deep (often >10m)	Shallow (<10m)	Determinant of stratification
Stratification	Usually persistent	Usually intermittent	Affected by depth and operations
Transparency	Higher	Lower	
TDS	Lower	Higher	
Nutrients	Lower	Higher	Component of TDS
Trophic State	Oligotrophic to mesotrophic	Eutrophic to hyper-eutrophic	Determined by nutrients

Table 4. Generalized comparison of Cold and Warm lakes for important environmental attributes.

Natural Lakes vs. Reservoirs

Most of the natural lakes in Colorado are very small and located at high elevation. Only eleven natural lakes are larger than 50 acres (Table 5). Quite a few natural lakes have been "submerged" when dams were built to add storage capacity to the lake. Most of the "lakes" on Grand Mesa, for example, have been dammed to add active storage. Twin Lakes is another well-known example where natural lakes were inundated by construction of a larger reservoir. In these examples, water levels can be manipulated frequently.

Lake	River System	Elevation, ft	Area, acres	Depth, ft	Latitude	Longitude	Location Note
Grand	Colorado	8367	470	265	40.24415	105.81486	
Lower Big Creek	North Platte	8997	315	55	40.92816	106.61074	North Park
Trappers	White	9604	287	174	39.98613	107.23122	Flat Tops

Lake	River System	Elevation, ft	Area, acres	Depth, ft	Latitude	Longitude	Location Note
Emerald	San Juan	10020	280	243	37.55314	107.44584	Pinos basin
San Cristobal	Colorado	8997	268	85	37.97152	107.29029	
Upper Big Creek	North Platte	9009	105	30	40.91335	106.61719	North Park
Upper Rainbow	North Platte	9854	90	92	40.64864	106.63461	Mt Zirkel Wilderness
Upper Marvine	White	9325	88	59	39.94082	107.36814	Flat Tops
Snowmass	Colorado	10980	82	121	39.11697	107.03406	Snowmass Peak
Lower Marvine	White	9320	65	57	39.94082	107.37945	Flat Tops
Roxy Anne	North Platte	10200	65	108	40.67205	106.65462	Mt Zirkel Wilderness

Table 5. Physical characteristics and locations of large (>50 acres) natural lakes in Colorado (mostly from Nelson 1970).

Small size and remoteness made most natural lakes ill-suited for meeting the needs of settlers, who lived mainly at lower elevations where there were few or no natural lakes. Construction of off-channel reservoirs began in the 1880s, initially for irrigation and later for municipal use (Knopf and Scott 1990). In the 20th Century, completion of massive water projects like the Colorado-Big Thompson (CBT) and the Aspinall Unit built some of Colorado's largest reservoirs. Reservoirs are now the predominant type of lake larger than 50 acres. For an inventory of larger reservoirs, see Ruddy and Hitt (1990).

Differences between lakes and reservoirs are related to the nature of the watershed, the effect of water management on hydrology, and the interaction of reservoir operation with thermal stratification (Table 6). Natural lakes are formed by geologic processes and were features of the landscape before human settlement. The watershed contributing to the lake is determined by natural topographic features, and watershed geology strongly influences water chemistry. Local topography establishes the elevation of the outflow, and the outflowing water comes entirely from the surface layer of the lake.

Feature	Lake	Reservoir	Comment
Geologic history	Pleistocene glaciation or older	Post-settlement	
Basin morphology	Deepest near middle	Deepest at dam	
Watershed	Well-defined natural watershed	Primary water source may be outside of local watershed	Off-channel reservoirs and trans-basin diversions affect expectations for load
Outflow	Surface	Bottom	Affects heat storage, stratification, and volume of hypolimnion
Residence time		Usually shorter than lakes	Water load tends to be higher for reservoirs, meaning nutrient loads also higher
Water level	Stable	Fluctuating	

Table 6. Generalized differences between lakes and reservoirs. Adapted from Cooke et al. (2005) and Kennedy (2001).

Natural lakes and main-stem reservoirs may have a very similar connection to the natural watershed and its influence on water quality. On the other hand, because development of water resources often involves moving water great distances from where it is available to where it is needed, water quality in an off-channel reservoir may be largely disconnected from, or unaffected by, conditions in the natural watershed. For example, Boulder Reservoir (700 acres) has a very small natural watershed (ca. 9 mi^2), which contributes less than 5 percent of the inflow. Some additional flow is diverted from the adjacent Boulder Creek watershed, but most of the water (ca. 90 percent) comes via the CBT system from watersheds on the western slope.

Natural lakes and reservoirs are subject to the same kinds of physical factors. Both kinds of lakes, if sufficiently deep, will exhibit thermal stratification during the summer. In the spring, water temperatures begin to rise, and the heat added to the lake is circulated evenly by the action of the wind. As day length and air temperatures increase, heat is added faster than it can be circulated by the wind, and layers form. The wind effectively circulates water (and heat) only in the upper layer (the *epilimnion* or mixed layer), which typically extends for several meters below the surface. Temperatures are essentially uniform throughout the epilimnion (Figure 3).

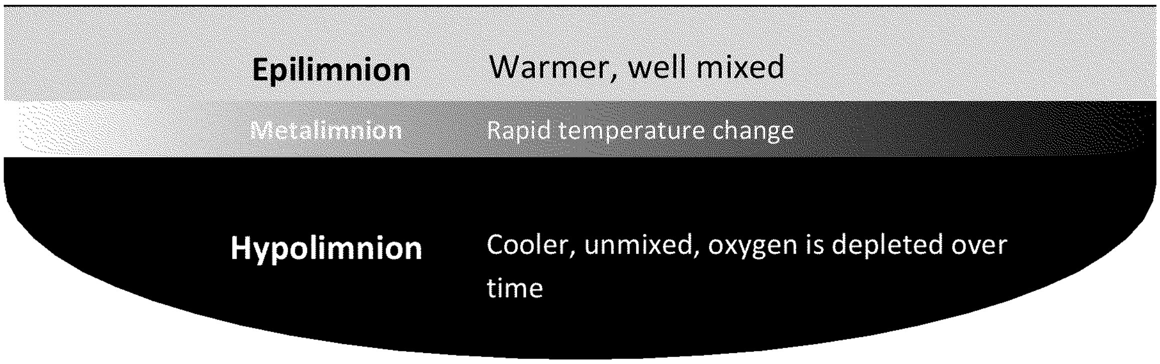

Figure 3. Diagram of summer layering in a thermally stratified lake. The top layer is the warmer epilimnion (mixed layer) and the bottom layer is the colder hypolimnion. The two layers are separated by the metalimnion where there is a str ong temperature gradient. Artwork by M May.

Below the reach of the wind, at the lower edge of the epilimnion, temperatures begin to decline rapidly with depth. The region of rapid temperature change is called the *metalimnion*. Within the metalimnion, the point at which the rate of temperature change is greatest is called the *thermocline*. Below the metalimnion is the *hypolimnion* in which temperatures are low, but often still declining slowly with depth because it is isolated from the wind that promotes mixing.

Although lakes and reservoirs may develop stratification in response to the same physical forces, the position of the outflow relative to the stratified layers has important implications that are not the same. The outflow for a natural lake is at the surface and draws only from the epilimnion. The rate of outflow is determined by the water level, which fluctuates relatively little. The outflow has no effect on layering in a natural lake. A reservoir that discharges exclusively via the spillway would behave much like a natural lake, but this is not a typical operating scenario.

Most reservoirs are designed to store and deliver water. Consequently, the main outlet (other than the spillway) is placed well below the level at which the reservoir is full. Water level can decrease rapidly when demand is high, and it can rise again as storage is augmented by runoff or diversion. Drawing down the reservoir usually has the effect of decreasing the volume of the hypolimnion. A smaller volume diminishes the capacity to absorb oxygen demand, and may reduce the stability of thermal stratification. However, as long as stratification persists, the behavior of the mixed layer (epilimnion) is likely to be much the same in reservoirs and natural lakes.

There are three reasons why the differences between lakes and reservoirs may not be great enough, or consistent enough, to warrant separate classification for the purpose of criteria development. The first is that algal growth occurs chiefly in the mixed layer, which develops and functions in essentially the same manner in natural lakes and reservoirs. If there is a consistent difference between the two types of lakes, it is more likely to be related to the development of the hypolimnion during summer stratification. During normal operation of reservoirs, water is released mainly from the hypolimnion rather than the mixed layer where algal growth occurs.

The second reason relates to potential differences in the way that nutrients, sediment, and water move through a reservoir (cf. Kennedy 2001). The argument rests on the assumption that the volume of a reservoir is small compared to the watershed that supplies the water, smaller than would be expected for a natural lake. According to this argument[19], water moves through a reservoir faster than through a natural lake of the same size; i.e., the hydraulic residence time is shorter and the water "load" is larger[20]. Other things being equal, when water load is high, corresponding nutrient loads and sediment loads also will be high. If the difference in sediment load, for example, results in consistently higher turbidity for reservoirs, it could lead to lower chlorophyll yield per unit phosphorus or nitrogen. In general, however, these differences are likely to be more important for restoration efforts than for development of criteria.

The third reason is the way in which water resource development and reservoir operations can blur distinctions between natural lakes and reservoirs. As mentioned previously, active storage capacity has been added to many natural lakes in Colorado by construction of dams (e.g., Twin Lakes and lakes on Grand Mesa). These formerly natural lakes are now subject to water level fluctuations, giving them reservoir-like features.

Grand Lake is a large natural lake where water management confers reservoir-like features. Every year, a large volume of water from outside of the natural drainage is introduced into the mixed layer, increasing water load (and decreasing residence time), nutrient load, and sediment load. The increased loads and associated changes in Grand Lake occur without causing fluctuations in lake level.

There are also reservoirs that are managed in a way that mimics attributes of natural lakes. Bear Creek Reservoir, for example, typically has a surface outflow and relatively little fluctuation in water surface elevation because it is operated chiefly for flood control rather than storage of water rights. Dillon and

[19] This reasoning may apply to many mainstem reservoirs, but it is not clear that it would apply equally well to off channel reservoirs.
[20] Hydraulic residence time is calculated as the lake volume (acre-feet) divided by the outflow rate (acre-feet per year) and has units of years. Water load is calculated as the inflow rate (acre-feet per year) divided by lake surface area (acres) and has units of feet per year.

Cherry Creek reservoirs typically are operated with little fluctuation in surface elevation during the summer as a concession to recreational interests.

The Division concludes that there are no compelling reasons to separate natural lakes from reservoirs as the general case for criteria development. The expectation is that most water quality impacts (e.g., elevated pH or algal blooms) will occur in the mixed layer, which behaves similarly in natural lakes and reservoirs. Also, water management can blur distinctions between the two types of lakes and thus diminish the likelihood that there will be consistent differences strong enough to shape criteria development. Of course, the option exists to develop site-specific criteria for any natural lake or any reservoir where the general case does not adequately characterize the responsiveness of algae to nutrients.

Lake Classifications Proposed or Adopted by Other States

States have considerable latitude for classifying lakes. A geographic basis that unites lakes with similar watershed characteristics is especially useful when a reference approach is applied to criteria development. Ecoregions were the primary basis for the Clean Water Act section 304(a) nutrient recommendations. Some states define categories according to ecoregion alone, while others use a second parameter to develop a cross-classification scheme (Table 7). South Carolina and Nebraska have ecoregions as the sole basis for classification, while Virginia, Minnesota, and Wisconsin use ecoregion in conjunction with other attributes. An ecoregion approach in Colorado could involve as many as six categories, with most of the additional partitioning occurring in the existing category for Warm lakes (most of the Cold lakes are in a single ecoregion).

State[21]	1st Classification	2nd Classification	Comment
AZ	Classified use (3)	Lake category (5)	
FL	Color (2)	Alkalinity (2)	
IA			Planning to apply criteria to all lakes >3 meters deep
MN	Ecoregion (4)	Fishery type (3)	Also lake type – lake, shallow lake, reservoir
NC	Fishery type (2)		Planning to add geographic classification
NE	Ecoregion (2)		
OR	Stratification (2)	Natural vs. reservoir	
SC	Ecoregion (3)		
VA	Ecoregion (3)	Fishery type (4)	2 natural lakes treated separately
WA	Ecoregion (5)		
WI	Stratification (2)	Hydrology (3)	Also incorporates some fishery types
WV	Fishery type (2)		
CO	**Aquatic Life (2)**		

Table 7. Systems of lake classification adopted or proposed by some states for development of lake nutrient criteria. Where two or more classification levels are used, not all combinations are possible (e.g., all fishery types are not present in all ecoregions of Minnesota or Virginia). The table does not reflect situations where s ize or residence time affects the classification.

Fishery type, which is one facet of the Aquatic Life use, is another common basis for lake classification (Table 7). Generally, these classifications recognize the importance of temperature as a determinant of

[21] Two-letter postal abbreviations are used throughout the tables for frequent references to states.

the fish community that can be sustained in a lake. For example, salmonids require cold water and bass require warm water. It is important to note that, in Colorado at least, the Aquatic Life use – Cold or Warm – is determined largely by temperature, and decisions about the management of the fishery may or may not coincide. For example, it is not uncommon for trout to be stocked in Warm lakes, but the stocking decision does not alter the Aquatic Life use.

Some states (e.g., North Carolina, Minnesota, and Virginia) have a category intended to protect the use of a lake as a potential trout fishery. It is also possible for the fishery type to be closely associated with ecoregion, and thus not require a separate basis for classification, as is the case for South Carolina.

Additional factors, such as the importance of deep-water oxygen during the summer, have prompted some states to establish additional categories where support for a fishery type involves more than temperature. For example, Minnesota has a separate category for lake trout, and Virginia and Wisconsin both acknowledge the importance of two-story fisheries.

Summer stratification is used explicitly by Oregon and Wisconsin, and it is incorporated implicitly in the classifications used by Arizona and Minnesota (probably also Virginia). The separation of natural from man-made lakes occurs explicitly in the classification schemes of Minnesota (although with almost no practical difference in the criteria), Oregon and Virginia. It also occurs by default where a state has few, if any, natural lakes, like South Carolina.

Hydrologic considerations have been incorporated only by Wisconsin, which has categories separating seepage lakes and drainage lakes, for example. A related issue is residence time, which is a function of two hydrologic properties – flow and volume. Two states – Minnesota and West Virginia – use a residence time of 14 days as a threshold for assessing a water body as a lake; a water body with a shorter residence time is assessed as a stream.

Several states use surface area as part of the classification for lakes, primarily to exclude very small lakes from assessment with numeric criteria. Size thresholds include 5 acres (Washington), 10 acres (North Carolina), 20 acres (Illinois, Massachusetts, and Nebraska), 40 acres (South Carolina), and 50 acres (Texas). South Carolina has a provision specifying that lakes smaller than the threshold be assessed against a narrative criterion.

Distinctions are sometimes made between lakes and reservoirs, but approaches are not uniform. For many states, especially those in areas unaffected by continental glaciation, most of the "lakes" of any size are man-made (i.e., reservoirs). Virginia, for example, has only two large natural lakes, each of which has site-specific nutrient criteria; the formal classification scheme for the criteria is based on reservoirs. Colorado is similar to Virginia in that there are only a few natural lakes of any size (Nelson 1970). Most states that recognize lakes and reservoirs as separate types of water bodies do not make distinctions with respect to application of criteria (e.g., Minnesota, Vermont).

Lake Classification Summary

The Division concludes that the existing classification of lakes with two categories, Cold and Warm Aquatic Life, is sufficient and appropriate for development of nutrient criteria. At the same time, the

Division recognizes that other situations, such as an interest in sustaining a fishery for lake trout or walleye, that might benefit from protection beyond that afforded by the two proposed categories. Because these species are introduced and managed by the Colorado Division of Wildlife (CDOW), rather than species inhabiting a particular lake category, no general categories are required. Instead, site-specific protections can be established based on proposals offered by the management agency or other interested parties.

Application of numeric nutrient criteria should initially be limited to lakes larger than 25 acres. Most of the lakes smaller than 25 acres are in the sub-alpine region, and there is little information available to characterize trophic conditions. The Division recommends assessing these small lakes against a narrative standard rather than with numeric criteria that have been developed for larger lakes.

In addition, the Division recommends setting a minimum residence time of 14 days as a condition for defining a water body as a lake. Water bodies with a shorter residence time should be assessed as streams.

4. Policy and the Approach to Nutrient Criteria Development

Nutrients are a leading cause of water quality impairments in lakes of the US (EPA 2009). The pervasive problem of cultural eutrophication has received much attention in the scientific and engineering literature, and the water quality consequences are well known. The solution to the problem – reducing nutrient loads to lakes –is understood, although spirited debate continues regarding the nutrient levels that are consistent with “fishable, swimmable” goals.

The regulatory approach to nutrients has been slow to develop at the state level. Colorado adopted site-specific standards for a few lakes in the 1980s and 1990s, but the scope has not been expanded. EPA first made a commitment to nutrient criteria development in 1997 when nutrient criteria were included in the Clean Water Action Plan. A technical guidance document for lakes was published in 2000 (EPA 2000a), and criteria recommendations for most of the nation (“304a criteria”) were released later the same year (e.g., EPA 2000b). States were asked to submit nutrient criteria development plans, which Colorado did in 2002.

Colorado has worked for a decade to develop a proposal for nutrient criteria. The task is difficult from a technical perspective, and it has proven contentious from a policy perspective. One of the challenges for nutrient criteria development is the non-toxic nature of the pollutants. Even ammonia, which is toxic at relatively high concentrations, is not toxic in the range of interest for preventing eutrophication. Thus, bioassays cannot define a “bright line” threshold for nutrient impairment, as they would for toxic pollutants.

The complexity of determining how much chlorophyll, phosphorus, or nitrogen is too much for a lake is not trivial. EPA has used the concept of “reference conditions” as a way of establishing what is expected in the absence of anthropogenic nutrient sources. The concept has attractive features in that it enables a quantitative characterization of ecosystem health, allows for regional variation, and provides a means of detecting the effect of stressors (Bailey et al. 2004; presented as "key features" of the reference condition approach for bioassessment, but equally appropriate here).

EPA favors the reference approach in technical guidance documents, and all 304a criteria were derived using the reference approach. However, Colorado has reservations about the applicability of the reference approach to our lakes, as well as a general concern about preserving policy options; these issues are addressed in more detail below. Deciding that the reference approach is not workable for Colorado places the responsibility on the State to develop a scientifically-defensible alternative.

The Division's proposal relies on selecting a target trophic condition that maintains ecosystem health, represents a balance of potentially competing interests, and minimizes the risk that excessive algal abundance will cause water quality impairments. In essence, trophic condition replaces reference condition as the basis for characterizing ecosystem health. Framing the goal in terms of trophic condition also makes it easier to understand the tradeoffs available from a policy perspective.

Trophic condition provides a well-understood and widely-used framework for characterizing water quality expectations in terms of algal abundance and nutrient supplies. It represents a continuum of lake productivity, rather than a specific archetype like reference conditions, and there may be a range of conditions within which water quality is not impaired. Within that range, there is potential for competition between interests. For example, fishing might benefit from higher algal abundance, but at the expense of swimming or aesthetic enjoyment that benefit from lower algal abundance (assuming that lower abundance translates into higher clarity).

Incorporating trophic condition as part of nutrient criteria development is both possible and appropriate because of the non-toxic nature of chlorophyll, phosphorus, and nitrogen. Chlorophyll alone is a sufficient basis for assessing trophic status, but, because it is a response variable, it is not a basis alone for implementation. Criteria are needed also for the causal variables (phosphorus and nitrogen), which serve as targets for discharge permit limits or for implementation of other management actions (e.g., total maximum daily loads (TMDLs)). Trophic condition provides the framework uniting causal and response variables.

Finding the right balance among potentially competing interests involves a stronger reliance on policy development than is the case for the reference approach. For example, a productive lake might be very desirable in terms of fishery yield, but the high level of algal abundance, with the attendant loss of water clarity, might be very unappealing to swimmers or boaters. Conversely, a crystal-clear lake would be very attractive for aesthetic reasons, but might disappoint most fishermen. Assessing the tradeoffs can be facilitated with guidance available from previous work, as described below.

Why the Reference Condition Approach Does Not Work for Colorado Lakes

In its Technical Guidance Manual (EPA 2000a), EPA relies on the characterization of reference conditions as the basis for defining the "least impacted" or "most attainable" condition in lakes. Reference conditions "set the upper bounds of what can be considered the most natural and attainable lake conditions for a specific region." The concept is attractive, especially where natural lakes are concerned, but the applicability of the concept to reservoirs and the methods used to characterize reference conditions deserve further scrutiny.

Like most states in the arid West, Colorado has many reservoirs (see Chapter on Description and Classification of Colorado Lakes). Reservoirs have been the focus for criteria development because, although there are many natural lakes in the mountains, only a handful of the natural lakes are larger than 50 acres. In addition, there are no natural lakes, and probably no permanent natural ponds, on the plains.

In theory, reference conditions could be developed for reservoirs, but in practice there are obstacles related to the logic of defining a "pristine reservoir" and the approaches available for establishing reference conditions. Reservoirs exist only because human presence demands more water than is available naturally. They are a recent feature of the landscape with highly modified connections to the watershed and a highly managed physical regime. Moreover, many are managed for recreational purposes that may or may not be well aligned with expectations for a pristine natural lake.

According to EPA's Guidance Manual, reference conditions can be established by one or more of three general approaches – direct observation, paleolimnological reconstruction, or modeling. All of the approaches can be applied to natural lakes, but choices are more restricted for highly managed reservoirs. A paleolimnological reconstruction, for example, is out of the question because reservoirs are man-made and of relatively recent origin.

An approach based on prediction or extrapolation from models also seems undesirable for Colorado. The modeling approach is aimed mainly at situations where there is a shortage of data or where models might be helpful in extrapolating reference conditions from lakes that vary in degree of degradation. It seems poorly suited to a situation in which the lakes are man-made and the water usually does not come from the natural drainage (i.e., making it difficult or impossible to extrapolate from natural background).

Even the Direct Observation approach, which can be developed from sites meeting specific criteria or from the distribution of all lake data, would be difficult to apply. Because most of our reservoirs are highly managed and subject to water level fluctuations, they would not qualify as reference sites[22]. That leaves only the lake population distribution approach that EPA (2000a) considers "especially relevant" for reservoirs.

When reference sites cannot be identified, reference conditions can be inferred from the set of all lakes. For each variable included in criteria development, the 25th percentile becomes the basis for characterizing reference conditions. EPA (2000a) refers to this as the "lake population distribution approach", and it is the primary basis for all 304a criteria developed for lakes.

[22] "Management actions, such as controlling water level fluctuations for hydropower or flood control, can significantly influence lake conditions. Reference lakes could be limited to those lakes that are in no way affected or are affected only in a limited way by such management activities." (EPA 2000a, page 6-3).

Despite widespread use in criteria recommendations, the basis for the 25th percentile is poorly established. The sole example presented in the guidance manual (EPA 2000a, page 6-10) shows that the 75th percentile of reference yields values for total phosphorus that are about 50 percent higher than the 25th percentile of all assessed lakes. However, to our knowledge, it has never been evaluated for reservoirs. An evaluation of percentiles for streams (Herlihy and Sifneos 2008) also suggests that it is often not a good choice.

In addition to issues about the percentile, there are questions of policy. By declaring that 25 percent of all lakes meet reference conditions, it implies that 75 percent are impaired. Although the Guidance Manual is cautious is saying the "reference conditions themselves are not specifically established as criteria", in practice it is hard to avoid that outcome.

The Division concludes that establishing reference conditions is not a reasonable policy goal for Colorado lakes. As an alternative, The Division recommends trophic condition as an expression of the policy goals that are consistent with the resource and protective of other uses.

Perspectives on Balancing Interests

Information is available for a brief evaluation of three different interests – fishing, swimming, and aesthetics (as indicated by property values). As will become evident, there is no single answer for any one of the interests, and visitors are rarely so single-minded about preferences (e.g., a clear mountain lake with a boundless supply of rainbow trout). In addition, expectations may not be the same for the two categories of lakes – Cold and Warm – for which criteria are being developed.

Trophic Condition and Fishery Yield

The relationship between fishery yield and lake productivity has been demonstrated in many studies (e.g., Oglesby 1977, Bachmann et al. 1996, Egertson and Downing 2004). The yield increases as the productivity of the lake increases across the spectrum of trophic condition. At the same time, however, increasing productivity is accompanied by a shift in the type of fishery that is supported, and the shift is not necessarily desirable.

As part of nutrient criteria development for Virginia, John Ney prepared a useful overview of information linking fishery type and chlorophyll concentrations.[23] Based on the literature review, he made recommendations for the chlorophyll concentrations as follows: coldwater fisheries (trout) should have chlorophyll less than or equal to 6 ug/L; coolwater fisheries (striped bass, walleye) should have chlorophyll less than or equal to 15 ug/L; and warmwater fisheries (mainly centrarchids) should have chlorophyll concentrations in the rage of 20-40 ug/L. In terms of trophic state, salmonids would be restricted to mesotrophic or oligotrophic conditions, coolwater fisheries could be successful at the low end of eutrophic, and warmwater fisheries could be sustained into the lower part of the hyper-eutrophic range.

[23] http://www.deq.virginia.gov/wqs/pdf/AAC05report.pdf; accessed 2 Dec 2010.

Another source[24], describes a similar pattern, but with slightly different boundaries. Salmonid fisheries are favored at the low end of the trophic spectrum, in part because those lakes are more likely to maintain dissolved oxygen in the hypolimnion. Cool water fisheries (e.g., walleye) are favored by mesotrophic conditions, and warm-water species like centrarchids are favored in eutrophic lakes. In hyper-eutrophic lakes, carp and rough fish are likely to dominate.

Some context regarding Colorado lakes is helpful at this stage because the existing classification scheme places constraints on what can be proposed. The existing classification scheme divides Colorado lakes into Cold and Warm categories based on expectations for the resident biota. For example, the definition for Cold Water Aquatic Life[25] explicitly mentions trout. In practice, a Cold lake usually can support salmonids, and a Warm lake usually can support warm water game fish. See *Description and Classification of Colorado Lakes* for more details.

Of course, the classification of uses is not dependent on fishery management decisions made by the responsible agency, the Colorado Parks and Wildlife[26] (CPW). Lakes and streams classified for Cold Aquatic Life are likely to be able to support trout, but the management agency (CPW) may or may not decide to manage a Cold water body as a trout fishery. Similarly, lakes and streams classified for Warm Aquatic Life are likely to be able to support warm water game fish, but the management agency may decide to operate the water body in a different manner, such as a put-and-take trout fishery.

Criteria development aims to support the use – Cold or Warm Aquatic Life – and that is not the same as maximizing fishery productivity. A healthy, productive salmonid fishery could be sustained in a lake that is oligotrophic or mesotrophic, but not in a lake that is more productive. Accordingly, the use would be supported if the target trophic condition for Cold lakes was set to mesotrophic. Similar conclusions have been reached by other states (see *Context from Other States*).

The target trophic condition for Warm lakes in Colorado is more difficult to specify because there are so many different kinds of warm water game fish. In general, management of Warm lakes in Colorado tends to focus more on species at the "cool water" end of the fishery spectrum (featuring species like walleye, wiper, and striped bass), rather than on the centrarchids and catfish that are more characteristic of true warmwater fisheries.

Fishery yield in Warm lakes should increase with increasing lake productivity, as it would in Cold lakes, but there is an additional concern about shifts in species composition. Increasing lake productivity tends to be accompanied by a shift to dominance by carp and other bottom-feeding fishes (Egertson and Downing 2004, Jackson et al. 2010). When catch rates of carp are high, catch rates of sport fish are low. Moreover, the poor water quality associated with an abundance of carp apparently is objectionable to anglers (Jackson et al. 2010). It appears that the tipping point, where changes in water quality lead to dominance by carp, is relatively abrupt.

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[24] http://www.secchidipin.org/tsi.htm ; accessed 11 March 2011
[25] "COLD WATER BIOTA means aquatic life, including trout, normally found in waters where the summer weekly average temperature does not frequently exceed 20 °C". 5 CCR 1002-31.5(8)
[26] Formerly known as the Division of Wildlife, but now in transition to become Colorado Parks and Wildlife.

Proposing eutrophic as the target trophic condition for Warm lakes is a prudent starting point that can be evaluated further in terms of other interests, as well as expectations for water quality. If the evidence warrants it, this target value can be adjusted up or down to balance competing interests.

User Perception and Water Clarity

Given a choice, most swimmers would probably prefer to see their toes on the bottom than to have the view obscured by algae. At the same time, however, locating a threshold of tolerance for clarity is difficult because there may be local or regional differences in expectations about transparency (Smeltzer and Heiskary 1990).

There are presently no clarity standards for Colorado lakes[27], so there is no simple basis for determining what conditions are acceptable in terms of visual perception, but there have been two surveys of user perceptions of water quality. The studies were not aimed at linking perceptions to specific water quality attributes like chlorophyll or Secchi depth, but they provide useful qualitative insights, nevertheless. At Cherry Creek Reservoir, the importance of visual appearance was shown by a survey in which users were asked to "define good water quality (unaided)", and 60 percent said "clear" (Howell Research Group 1997).

An earlier study of Chatfield and Cherry Creek reservoirs (Aukerman 1982) showed that users could detect differences in water quality. To the extent that perceptions of water quality can be equated with clarity, as suggested in the 1997 survey of Cherry Creek Reservoir, users had very different impressions of the two reservoirs. For example, 38 percent of boaters chose Chatfield (median summer Secchi depth of 2.0 meters) on the basis of "water quality", but almost no one cited water quality as a reason for choosing Cherry Creek Reservoir (median summer Secchi depth of 0.9 m).

A recent literature review in support of lake criteria development by Virginia[28] suggests that Secchi depths less than 1 meter generally are considered undesirable. From the standpoint of chlorophyll concentrations, a user perception study of Texas reservoirs found that the average chlorophyll associated with "enjoyment … substantially reduced" was about 27 ug/L (TWCA 2005). A similar study in Florida placed the threshold at about 30 ug/L (Hoyer et al. 2004). Those two chlorophyll values are close to the upper boundary for eutrophic lakes.

For the purpose of evaluating policy options, a Secchi depth of 1.0 meter is probably the limit of what is desirable from the standpoint of user perceptions. It is also consistent with the upper boundary for eutrophic lakes according to the OECD scheme (the range for minimum Secchi values is given as 0.7-1.5; OECD 1982). However, greater clarity may be expected in montane lakes.

Aesthetic Values and Water Clarity

The aesthetic value of a lake can be diminished by the sight or smell of excessive algal abundance, but quantifying the effect for regulatory or monetary purposes is difficult. Few states assess aesthetic quality in a formal way, but it is instructive to consider their approaches. Oklahoma has an aesthetics

[27] Although there are no criteria applicable to Colorado lakes in general, there is a site-specific criterion of 4.0 meters for Grand Lake that is slated to become effective in 2015.
[28] AAC_Addendum2_2005, http://www.deq.virginia.gov/wqs/rule.html#NUT2 , accessed 9/8/2010.

beneficial use and links the decision about attainment to the outcome of a nutrient impairment study; if the Carlson Trophic State Index (TSI)[29] is less than 62, the aesthetics use is considered attained (ODEQ 2010). The TSI threshold for this determination corresponds to a trophic condition slightly higher than eutrophic according to Oklahoma's "Lake Trophic State Categories", which places the upper bound for eutrophic at TSI = 60.[30]

The State of Illinois assesses aesthetic quality on the basis of an index (AQI; aesthetic quality index) that includes the Carlson TSI as one of three components (IEPA 2008). In cases where the evaluation is made solely on the basis of the TSI,[31] aesthetic quality is "fully supported" when the TSI is less than 60, which is very similar to the eutrophic threshold for Oklahoma lakes.

The importance of aesthetics has also been translated into economic valuation through a number of studies. These may not help with setting thresholds, but they demonstrate that eutrophication results in external costs. Especially relevant to lakes are studies showing the effect of reduced clarity on lakeshore property values (e.g., Steinnes 1992, Pretty et al. 2003, and Dodds et al. 2009). In their analysis of economic impacts of eutrophication on lakes and rivers in the US, Dodds et al. (2009) found that the "greatest economic losses were attributed lakefront property values … and recreational use."

Balance

Colorado has opted to develop nutrient criteria that define the trophic conditions appropriate for lakes in each of two existing categories – Cold and Warm. The decision to work with trophic condition rather than reference condition opens a more explicit role for policy-making, but also introduces new challenges. Specifying the target trophic condition is more difficult because it involves finding the right balance among potentially competing interests. At the same time, however, trophic condition provides a stronger biological framework for uniting nutrients, algae, and water quality implications.

Target trophic conditions were initially based on what is considered ideal, from a fisheries management perspective, for Cold and Warm lakes. This approach works reasonably well for Cold lakes because a healthy salmonid fishery can be expected in a lake that is oligotrophic or mesotrophic, and the lake also appears aesthetically pleasing. The situation is somewhat different for Warm lakes where the ideal condition for a warmwater fishery – eutrophic or even the lower range of hyper-eutrophic – may cross a tolerance threshold for water clarity and may place the lake at risk for other water quality impacts.

A reduction in trophic condition below what might be ideal for the productivity of the fishery does not mean the use would be impaired. As mentioned previously, the target condition for Warm lakes is

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[29] See Chapter on "Eutrophication: Process and Problem" for general information on trophic condition and a comparison of different classification schemes. See http://www.secchidipin.org/tsi.htm for details regarding calculation of Carlson TSI.

[30] Oklahoma calculates the TSI on the basis of the chlorophyll concentration; when chlorophyll is 25 ug/L, the TSI would be 62. Carlson also developed an equation for TSI based on Secchi depth; back-calculating from TSI=62, the corresponding Secchi depth would be about 0.9 meters.

[31] The three components are added together to get total AQI points for Oklahoma lakes. If macrophyte coverage is minimal (<5%) and NVSS concentration is low (<3 mg/L), the AQI is equal to the TSI.

defined as eutrophic, *or less productive*. The obligation is to protect the use and not to maximize fishery production.

Selecting target trophic conditions of mesotrophic (or less productive) for Cold lakes and eutrophic (or less productive) for Warm lakes provides a reasonable starting point for development of numeric criteria. However, before formal recommendations can be made for numeric values, it is important to assess specific water quality implications of the target trophic conditions. In addition, it is necessary to characterize the linkage between algal abundance, which is the primary basis for characterizing trophic condition, and nutrients, which are the main determinant of algal abundance in lakes. After these tasks have been completed it may be necessary to revise target trophic conditions to reduce the risk of exceeding other criteria, such as pH.

5. Characterizing Algal Abundance

The algal communities (also called phytoplankton) in Colorado lakes are comprised of many species. Several hundred species have been identified in samples taken by the Division, and more species will be encountered as sampling continues. The details of taxonomic composition are of intrinsic interest and can be useful for anticipating water quality problems (e.g., species that cause taste and odor problems), but most of the effort for nutrient criteria development has been focused on a widely used aggregate measure of algal abundance – chlorophyll concentration[32].

Chlorophyll is the primary “pigment” that all algae use for photosynthesis. It is found within the algal cells and is responsible for the green color of algae. It is particularly useful as a measure of algal abundance because it is found only in the living cells. After an algal cell dies, the chlorophyll disappears very rapidly through chemical degradation even though the cell may remain suspended in the water column for a long time.

Chlorophyll concentration can change rapidly as the algal populations wax and wane in a lake. The variability may appear random, but it is determined by a continuous interaction between processes that stimulate growth (e.g., nutrients and light) and those that result in losses (e.g., grazing and other forms of mortality). In addition to the short-term variability, there may be broader patterns related to seasons. A descriptive overview of variability within a lake is a useful precursor to a more quantitative analysis of patterns of variability.

Variations in abundance are of great interest from a regulatory perspective because of the need to include duration and frequency components in each standard. Where seasonal patterns of variation are consistent, they can be used to define the averaging period (duration component) of the standard. In addition, variability over different time intervals is important for defining recurrence intervals that are

[32] Although several forms of chlorophyll are present in the various taxonomic groups of algae, chlorophyll *a* is the primary photosynthetic pigment in all algae and Cyanobacteria (the so-called blue-green algae); the other chlorophylls are accessory pigments. In this document, all reference to chlorophyll is meant to refer exclusively to chlorophyll *a*.

central to specifying the allowable frequency of exceedance. Time intervals could be chosen to evaluate daily events like elevated pH or seasonal events like summer average[33] chlorophyll concentration.

Analysis of variability in algal abundance is carried out in two steps. The first step defines seasonal patterns to determine the relative merits of focusing regulatory attention on one season or another. Most states that have adopted nutrient criteria conduct assessments over a part of the year (e.g., summer, growing season, peak season of productivity, or assessment period). Colorado also has historical precedents for defining a season within which averages are assessed.

The second step for assessing variation is to characterize the magnitude of variation within and among seasons. It is well known that variability in chlorophyll measurements tends to increase as the average concentration increases (e.g., Walker 1985). A quantitative relationship between the average and the variance of chlorophyll concentrations in Colorado lakes can be used to predict the frequency of exceedances for individual values during one summer or for summer averages during an assessment cycle. Both components of variation are potentially useful for determining the protectiveness, on different time scales, of the selected criterion value.

Descriptive Overview of Algal Abundance in Individual Lakes

Several Colorado lakes have been sampled frequently for many years, and they present good opportunities for examining time series of algal abundance. Arvada Reservoir is sampled throughout the year unless ice conditions are unsafe. Sampling is generally biweekly from April through October or November and monthly for the rest of the year. A time series of data from 1994-2009 shows that chlorophyll concentrations are less than 6 ug/L most of the time, although there are occasional high values (Figure 4). There appears to be some seasonal pattern to algal abundance, but it is difficult to define it from the time series.

[33] The term "average" is used throughout the document as the common term for the "arithmetic mean". This usage is consistent with definitions in Sokal and Rohlf (1995).

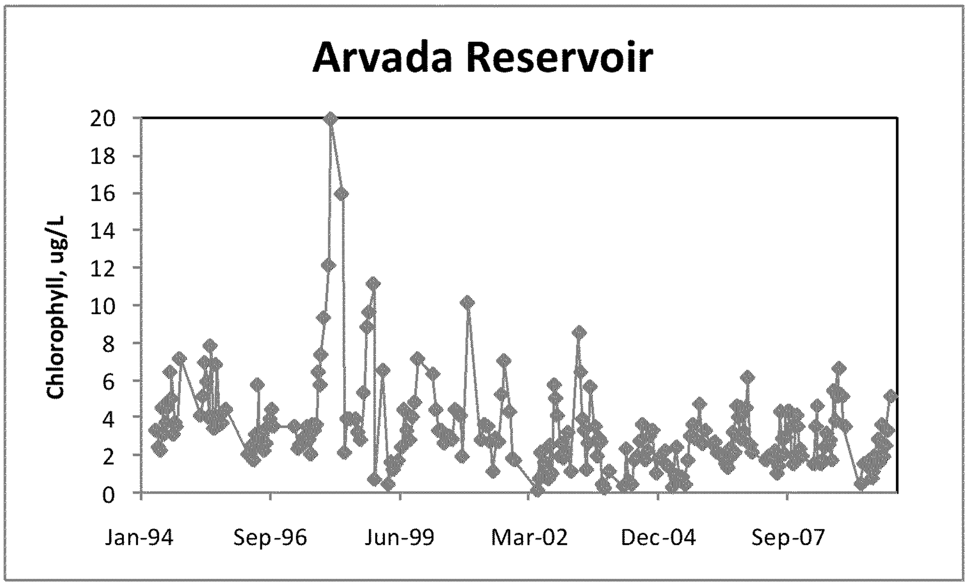

Figure 4. Time series of chlorophyll concentrations in Arvada Reservoir, 1994-2009.

A better way of detecting persistent seasonal patterns in the data is to overlay all years by plotting against day of year (ordinal day). Seasonality does not appear to be strong for algal abundance in Arvada Reservoir (Figure 5). Variability tends to be higher in the winter months, and chlorophyll concentration tends to increase over the summer, but it is difficult to discern how the typical value changes from month to month.

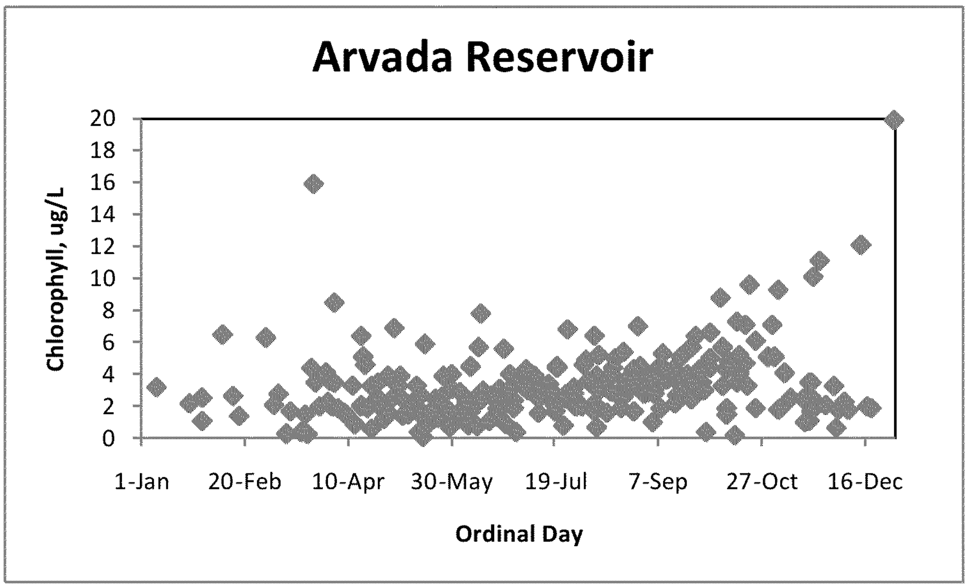

Figure 5. Seasonal variation in chlorophyll concentrations in Arvada Reservoir. All years (1994-2009) are combined and plotted against ordinal day to highlight seasonal patterns.

A sharper image of seasonal patterns can be obtained by creating box plots that show the distribution of chlorophyll concentrations measured in each of the twelve months, aggregated over the sixteen years in the period of record. The general pattern begins with low, but relatively variable, concentrations in the winter, followed by more consistently low concentrations in the spring (Figure 6). The variability of chlorophyll concentrations in each month is indicated by the height of the "box" (defined by the 25th and 75th percentiles of values in each month) and the extent of the "whiskers" (the tips represent the 5th and 95th percentiles). Concentrations rise from July through October.

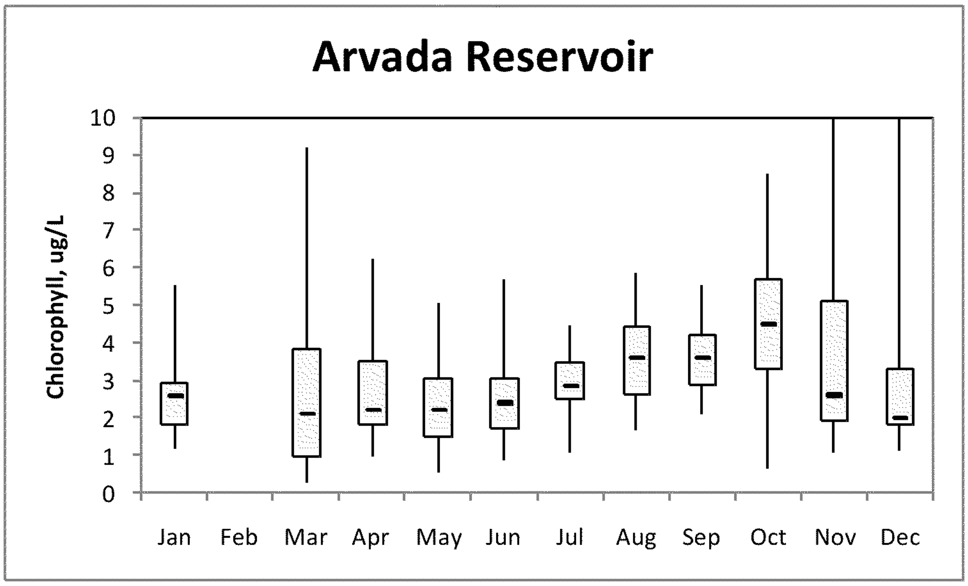

Figure 6. Box plot of monthly chlorophyll concentrations in Arvada Reservoir. All years are combined. The few samples from February were combined with those available for January to provide enough data to construct the box plot. The boundaries of each box show the 25th (bottom of box) and 75th (top of box) percentiles of chlorophyll concentrations in each month. The horizontal bar within each box corresponds to the median concentration. The tip of the l ower whisker is the 5th percentile and the tip of the upper whisker is the 95th percentile.

It is also apparent that concentrations in each month tend to be skewed to the high side; the median tends to be low in each box rather than near the middle, and the upper whisker tends to be longer than the lower whisker (Figure 6). These characteristics suggest that the chlorophyll concentrations conform more closely to a lognormal, rather than a normal, distribution. When the data are plotted on a logarithmic scale, the distributions become more symmetrical (Figure 7). Because the distinction is important for statistical reasons, logarithmic scales appear frequently in the figures and statistical procedures used in criteria development.

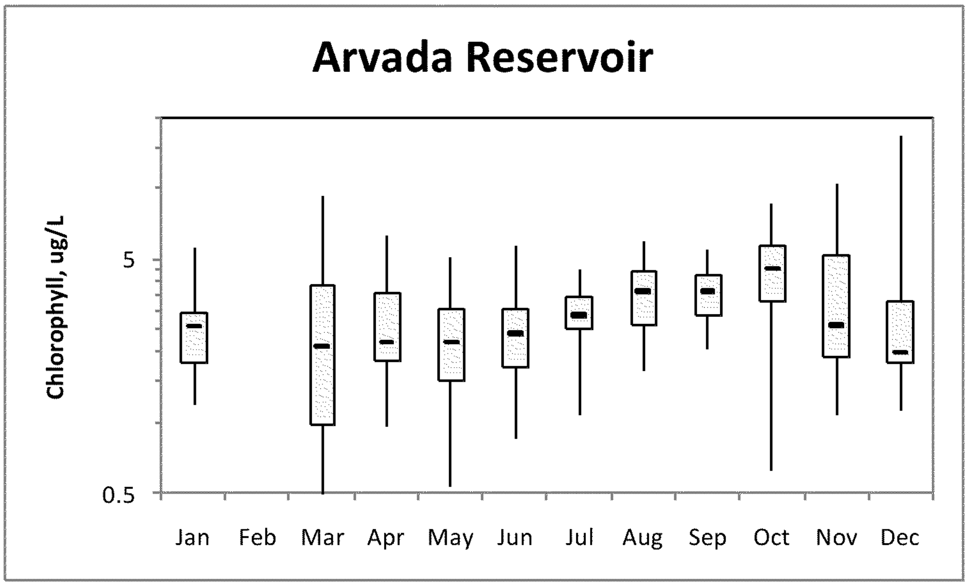

Figure 7. Box plot of monthly chlorophyll concentrations in Arvada Reservoir. All years are combined. Same as Figure 6 except chlorophyll is plotted on a logarithmic scale.

A similar compilation of chlorophyll concentrations is presented for Cherry Creek Reservoir. The time series suggests that there is an underlying seasonal pattern (Figure 8), which becomes more evident when the data are plotted against ordinal day (Figure 9). As is apparent from the box plots (Figure 10), algal abundance tends to be lowest in June and highest in January-February.

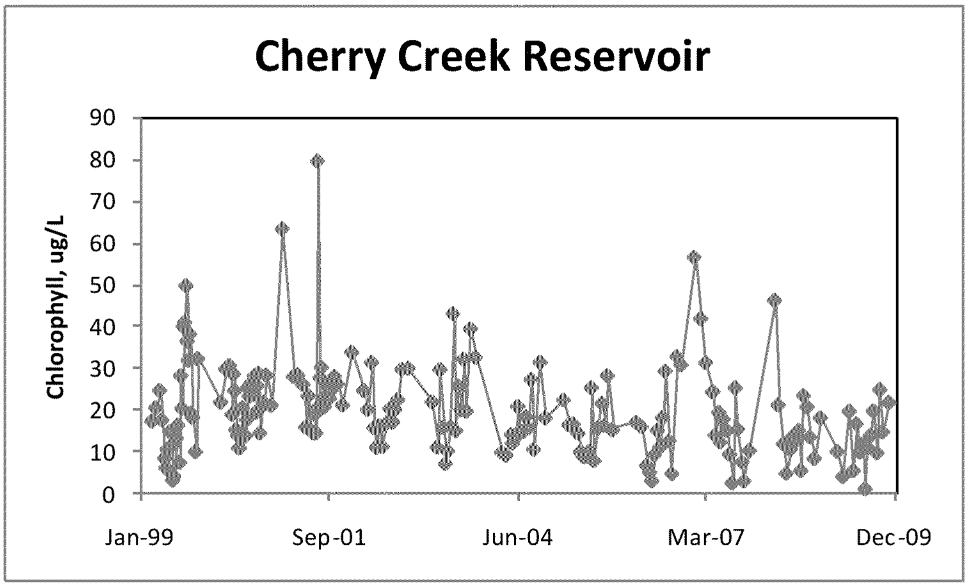

Figure 8. Time series of chlorophyll concentrations in Cherry Creek Reservoir, 1999-2009.

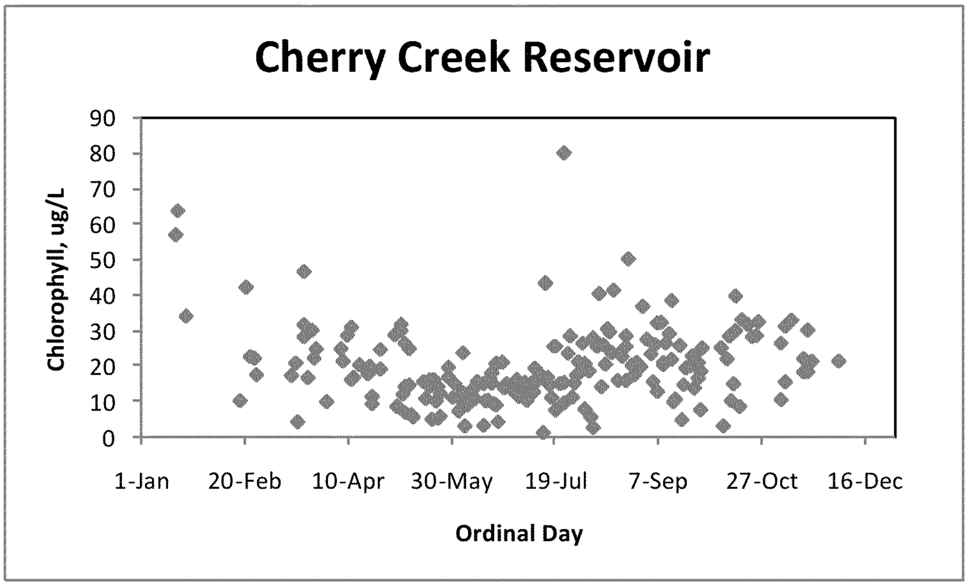

Figure 9. Seasonal variation in chlorophyll concentrations in Cherry Creek Reservoir. All years (1999-2009) are combined and plotted against ordinal day to highlight seasonal patterns.

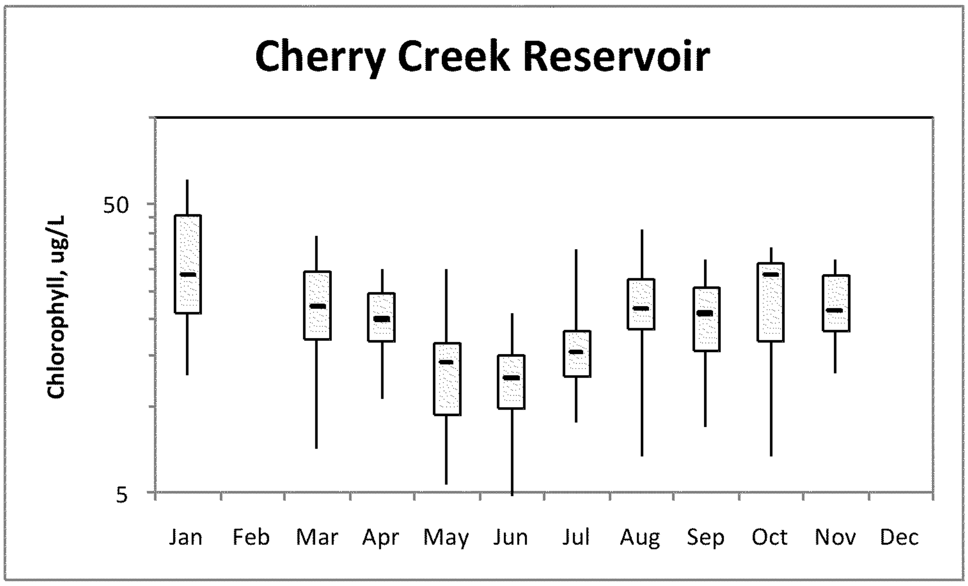

Figure 10. Box plot of monthly chlorophyll concentrations in Cherry Cre ek Reservoir. All years are combined. The few samples from February were combined with those available for January to provide enough data to construct the box plot. The same approach was taken for November and December. Chlorophyll concentrations are s hown on a logarithmic scale. The boundaries of each box show the 25th (bottom of box) and 75th (top of box) percentiles of chlorophyll concentrations in each month. The horizontal bar within each box corresponds to the median concentration. The tip of t he lower whisker is the 5th percentile and the tip of the upper whisker is the 95th percentile.

Barr Lake also has a very strong sampling record, and the data show strong seasonality in algal abundance that is evident even in the time series (Figure 11). The seasonal plot shows uniformly low algal abundance in late spring (Figure 12), and the box plot identifies April and May as the time of lowest algal abundance (Figure 13).

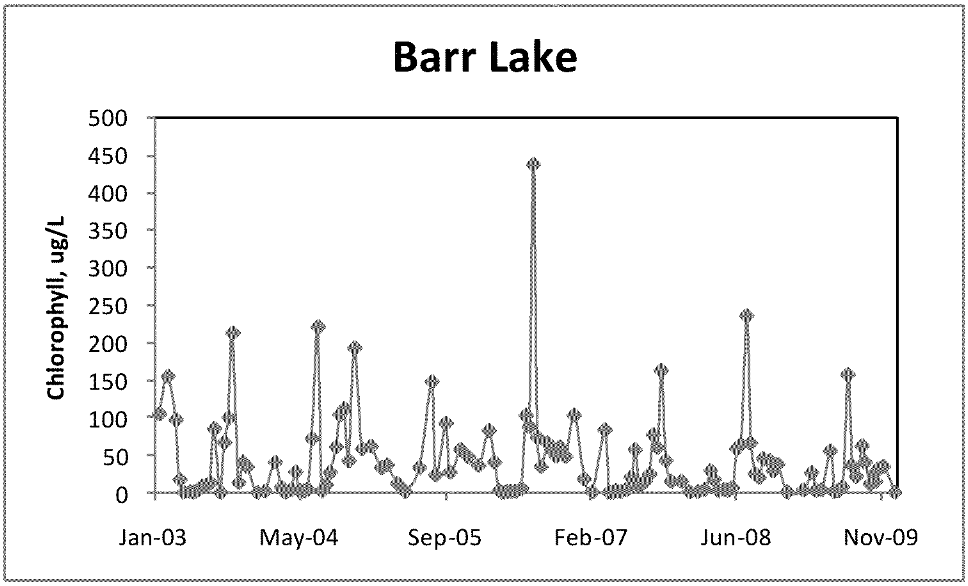

Figure 11. Time series of chlorophyll concentrations in Barr Lake, 2003-2009.

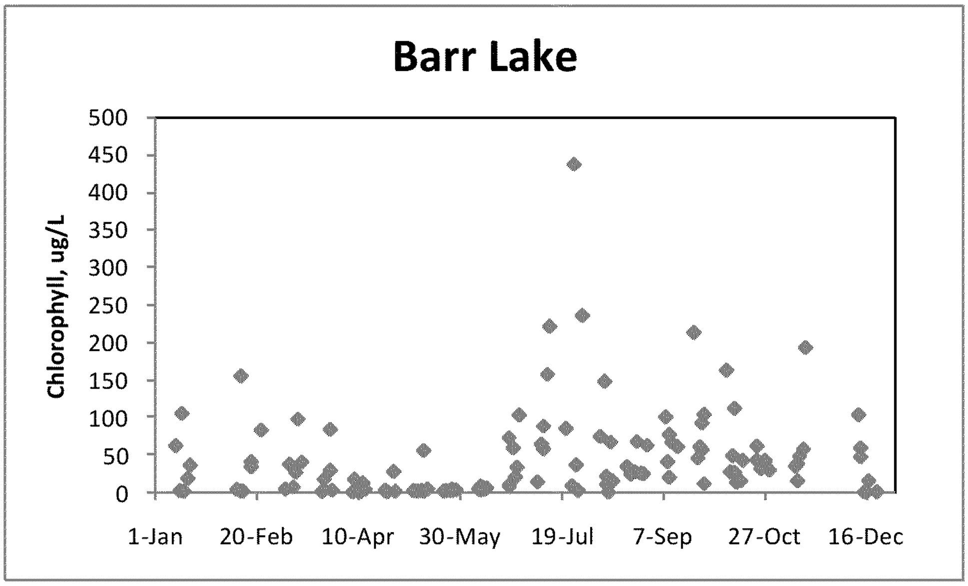

Figure 12. Seasonal variation in chlorophyll concentrations in Barr Lake. All years (2003-2009) are combined and plotted against ordinal day to highlight seasonal patterns.

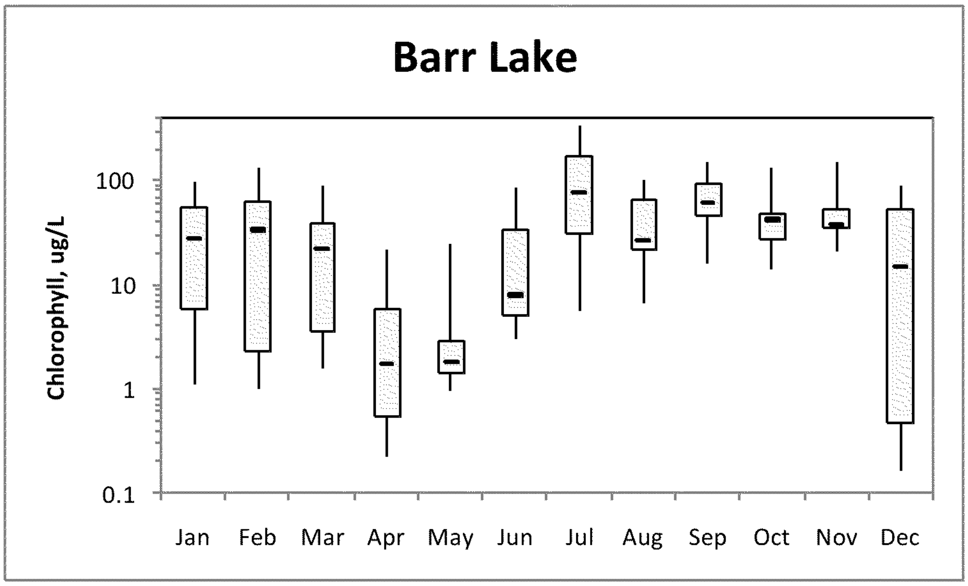

Figure 13. Box plot of monthly chlorophyll concentrations in Barr Lake. All years are combined. Chlorophyll concentrations are shown on a logarithmic scale. The boundaries of each box show the 25th (bottom of box) and 75th (top of box) percentiles of chlorophyll concentrations in each month. The horizontal bar within each box corresponds to the median concentration. The tip of the lower whisker is the 5th percentile and the tip of the upper whisker is the 95th percentile.

If there were no seasonality in algal abundance, the choice of an averaging period would matter little. However, abundance tends to be seasonal in most Colorado lakes, with minimum abundance often occurring in the spring and peak abundance in late summer or even in the winter. The basis for defining an averaging period depends on a variety of factors including seasonal abundance patterns and use protection, as well as logistical considerations.

Averaging Period

Each water-quality criterion has a duration component that specifies the period of time within which ambient concentrations are averaged for comparison with the allowable concentration (EPA 1991). For most criteria in Colorado, typical averaging periods are one day (acute) and thirty days (chronic). Historically, however, nutrients have been treated differently in Colorado and most other states.

When site-specific nutrient criteria were adopted for selected Colorado reservoirs, the averaging period was intended to represent the "growing season." Although the term growing season is widely used in limnological literature, and it appears in water quality regulations in some other states, there does not seem to be a formal basis for deciding which months should be included in the growing season for lakes. In practice, the growing season for Colorado lakes was defined as July-September or July-October.

Most people probably have an inherent sense of what "growing season" means, if only by analogy to agriculture. It is the period of time within which a particular crop can be grown at a particular location, and it is a function of climate (meaning temperature), light and rainfall. The Natural Resources Conservation Service (NRCS, 1995) has a formal definition that is based on soil temperatures. In Colorado, assuming that water can be made available, the terrestrial growing season extends throughout frost-free months, which are determined largely by elevation. Such a definition is not readily transferred to lakes, however, because even ice cover does not prevent algae from growing throughout the winter months. In addition, because algal generation times are relatively short, the community produces many more than a single "crop" each year.

In the course of developing nutrient criteria, states have reached different conclusions about the months within which concentrations will be averaged (Table 8). It is common, but not universal, to characterize the averaging period as a growing season that begins in April or May and ends in September or October. Flexibility in the definition of the averaging period is valuable on a national scale, because it allows states to tailor criteria to the patterns of variability observed in their lakes.

State	Months	Description
AL	Apr-Oct	Growing season (April-September for Tennessee River basin)
AZ	May-Sep	Peak season of productivity for cold water lakes
AZ	Apr-Oct	Peak season of productivity for warm water lakes
CA	May-Oct	Site-specific
CO	Jul-Sep	Growing season for Chatfield, Cherry Creek, and Bear Creek reservoirs
CO	Jul-Oct	Growing season for Lake Dillon
CO	Mar-Nov	9-month average for Standley Lake
FL	All	Annual
GA	Apr-Oct	Growing season
IA	May-Sep	Summer recreation season (Memorial Day to Labor Day)
MN	Jun-Sep	Summer growing season (mid-May-September); assess June-September
NE	Apr-Sep	Growing season
VA	Apr-Oct	Monitoring period
WI	Jul 15 – Sep 15	Summer index period
WV	May-Oct	Growing season

Table 8. Averaging periods proposed or adopted by selected states for assessment of algal abundance (chlorophyll concentration) in lakes. The averaging period is not always characterized as a "growing season."

Colorado previously has adopted an averaging period that begins in July for four of the five lakes with site-specific standards. No formal studies are known to have been conducted to justify the averaging period, but it is likely that the time window made allowances for seasonal events like ice-out or spring runoff that influence the potential for algal growth. The intent probably was similar to that expressed in Wisconsin's integrated report (WDNR 2010): the period of time "when the lake responds to nutrient inputs and achieves maximum aquatic plant growth."

Standley Lake does not fit the mold used for the other site-specific standards in Colorado largely because the focus was on protection of the water supply use rather than aquatic life or recreation. The original proposal for Standley Lake had been for an annual averaging period based on concerns about high algal abundance during the winter months. However, due largely to concerns about safety during winter sampling, a 9-month averaging period (March-November) was selected as a reasonable compromise.

Alternative averaging periods can be proposed based on the way in which excessive abundance might affect particular uses. From the standpoint of aquatic life protection, for example, average chlorophyll concentration can be an indicator of potential for habitat impairment. When a lake is stratified, algal biomass produced in the epilimnion settles into the hypolimnion where it decomposes. As long as stratification persists, the oxygen consumed by decomposition is not replaced. The greater the production of algal biomass in a lake, the greater the demand is for dissolved oxygen in the hypolimnion. When oxygen concentrations fall too low, the habitat is impaired with respect to the aquatic life use. The appropriate averaging period for chlorophyll would thus correspond to the *stratification season*, and defining the duration of stratification becomes important for nutrient criteria development.

The averaging period appropriate for protection of the water supply use might be *annual*. For example, Oklahoma has proposed assessment of average chlorophyll over a period of at least a year, and the site-specific standard for chlorophyll in Standley Lake was originally proposed as an annual average. Assessing over a full year may make sense, at least in concept, for water supplies because water treatment plants typically operate throughout the year, and concerns about disinfection by-products might arise at any time.

Protection of the water supply use also may depend on preventing blooms, which may form and disappear on a time scale that is very short with respect to typical averaging periods. Excess algal abundance may be accompanied by formation of cyanotoxins or taste-and-odor problems, both of which are potentially detrimental to drinking water quality. These problems can occur at any time during the year, although blue-green algae, which are the source of cyanotoxins and some taste-and-odor compounds, tend to be more common during the warmer months (see *Algal Abundance and Water Quality Impacts*).

For primary contact recreation, the chief threat occurs with the formation of algal blooms, especially when also associated with toxin production. Concern about the effect of blooms on primary contact recreation is limited chiefly to those months when swim beaches are open. In Colorado (also for Iowa), the principal focus would be on the period from Memorial Day to Labor Day, which is also the schedule for monitoring for bacteria at Colorado swim beaches. The *recreation season* for measuring chlorophyll would thus include June to August.

A summer growing season is defined in each of the existing nutrient control regulations. The regulations for Cherry Creek, Chatfield and Bear Creek reservoirs define the growing season as July-September, and the regulation for Dillon Reservoir uses July-October. The more common definition of *summer season* – July-September – is used here.

Four alternative time periods are evaluated below: annual, stratification season (depends on elevation, as explained next), recreation season (June-August), and summer (July-September). Ideally, comparison of the averaging periods would be based on a very comprehensive data set that included frequent measurement of chlorophyll in all months of the year. With such a data set, it would be a simple matter to determine the maximum or compute the average within any averaging period of interest. At the same time, it would be of great practical value if it could be shown that sampling within a smaller time window would provide the same level of protection at reduced cost and without the safety concerns of sampling through the ice, for example. Is there a single averaging period that provides an efficient basis for effective protection of all uses?

Duration of Stratification in Colorado Lakes

Before all averaging periods can be compared, the stratification season must be defined. The duration of stratification is a key consideration for delimiting the seasons to be compared on the basis of chlorophyll concentrations. Lakes that are deep enough will stratify, and the duration may influence development of algal abundance. The resident algae are distributed throughout the mixed layer. As long as stratification persists, the thickness of the mixed layer will be similar to that of a lake that does not stratify. After stratification disappears in the fall, algae in a deep lake will be distributed over the entire water column. The analysis of stratification is based on examination of temperature data from individual lakes, with a goal of identifying geographical patterns in the timing of stratification.

Comprehensive temperature records from several Colorado lakes are used to establish the timing of stratification (Table 2). The temperature difference between the top and bottom layers[34] is used to detect the seasonal pattern of stratification, which is assumed to persist as long as the temperature difference exceeds 2^{o}C. Inverse stratification, which develops under ice cover, is not considered.

Lake	Elevation	Start	End	Duration, weeks	Period of Record	Data Sources[35]
Dillon	9017	24 May	26 Oct	22	1990-2008	SWQC
Grand	8367	9 May	1 Nov	25	1997-2008	USGS,USBR, NCWCD
Granby	8285	17 May	23 Oct	23	1997-2008	USGS,USBR, NCWCD
Barker	8187	25 May	10 Oct	20	2000-2009	Boulder
Green Mountain	7950	19 May	14 Oct	21	1990-2009	SWQC
Wolford Mountain	7490		16 Oct		1996-2010	USGS
Aurora	5930	5 May	1 Oct	21	1998-2009	Aurora
Carter	5763	29 Apr	13 Oct	24	1990-2009	USGS, NCWCD
Arvada	5759	27 Apr	11 Oct	24	1997-2009	Arvada
Bear Creek	5553	9 Apr	9 Sep	22	1990-2009	BCWA
Cherry Creek	5550	12 Apr			1996-2009	CCBWQA
Standley	5509	17 Apr	21 Sep	22	1995-2009	Westminster
Seaman	5481	5 Apr	30 Sep	25	2000-2008	Greeley
Chatfield	5432	14 Apr	24 Aug	19	1993-2009	Chatfield Basin Authority
Horsetooth	5430	14 Apr	10 Oct	26	1990-2008	USGS,USBR, NCWCD
Boulder	5173	25 Apr	18 Sep	21	1993-2009	Boulder
Loveland	5006	19 Apr	3 Oct	24	1998-2008	Greeley
Boyd	4958	18 Apr	20 Sep	22	1998-2008	Greeley
Pueblo	4826	28 Apr	11 Sep	21	1990-2010	USGS

[34] The mixed layer temperature is usually measured at one meter, and the bottom layer temperature is the minimum from the profile.

[35] Abbreviations include US Geological Survey (USGS), US Bureau of Reclamation (USBR), Northern Colorado Water Conservancy District (NCWCD), Summit Water Quality Committee (SWQC), Cherry Creek Basin Water Quality Authority (CCBWQA), and Bear Creek Watershed Association (BCWA).

Table 9. Timing of stratification in a selection of Colorado lakes ordered by elevation. The listed start and end dates are typical; actual dates vary among years. See text for explanation of threshold for stratification.

Strong patterns of summer stratification are evident in most lakes deep enough to stratify. Lake Granby provides a good example of stratification in a deep lake at high elevation (Figure 14). Stratification follows a repeatable pattern with relatively little variation among years. Other lakes at high elevation show similar patterns, although there may be more variability in the start and end dates.

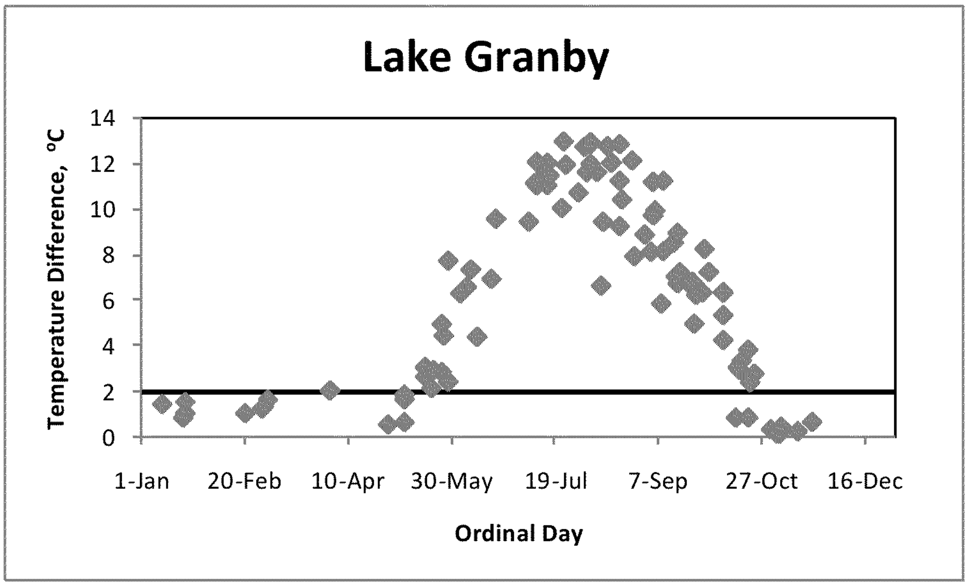

Figure 14. Seasonal pattern of thermal stratification in Lake Granby defined on the basis of the difference in temperature between top and bottom layers. Data from several years are plotted against ordinal day to highlight the seasonal pattern.

Lakes at low elevation show similar patterns, and Arvada Reservoir is a good example (Figure 15). There tends to be more variability in the timing of stratification at low elevation, possibly because the lakes tend to be shallower. Not all of the low elevation lakes show persistent stratification. Cherry Creek Reservoir, for example, is unlikely to stratify for more than a few weeks at a time, and even the intermittent stratification does not extend beyond July. Some low elevation lakes like Bear Creek Reservoir or Cherry Creek Reservoir are now de-stratified by aeration. Finally, there are some relatively shallow lakes, like Boulder or Chatfield, that start the season with strong stratification, but lose it early as the lake is drawn down.

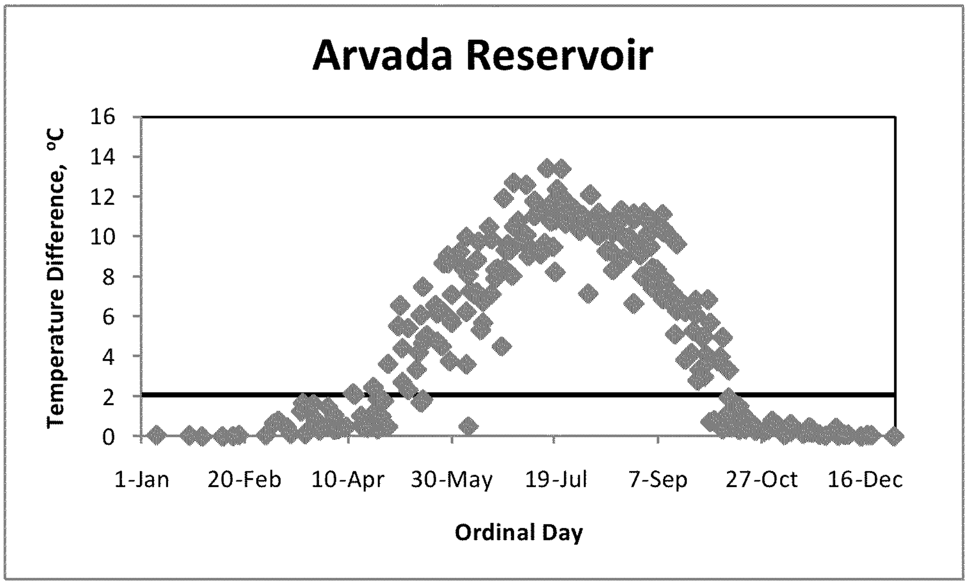

Figure 15. Seasonal pattern of thermal stratification in Arvada Reservoir defined on the basis of the difference in temperature between top and bottom layers. Data from several years are plotted against ordinal day to highlight the seasonal pattern.

There is enough information to make some generalizations about stratification in Colorado lakes. Persistent stratification is likely when depth remains greater than about 10 meters. The timing of stratification appears to be strongly related to elevation (Figure 16). Lakes at low elevation (less than about 6,000 feet) usually develop stratification during April, and stratification persists for about five months. Lakes at high elevation (greater than about 7,500 feet) do not begin to develop stratification until a few weeks after ice melts, usually in May. Stratification in these lakes also persists for about five months.

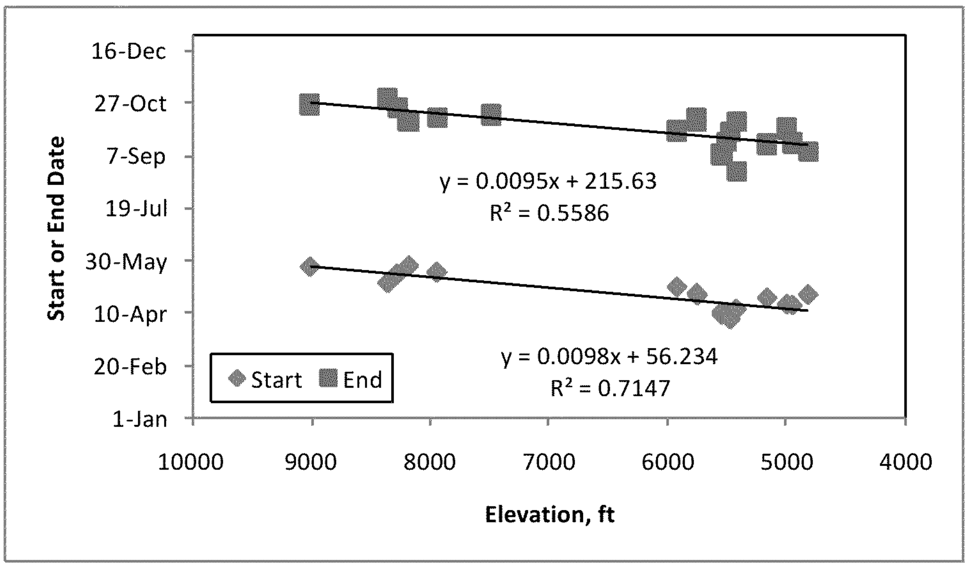

Figure 16. The timing of summer stratification as a function of elevation. See Table 9 for data from individual lakes.

In approximate terms, stratification for low elevation lakes extends from May through September, and stratification for high elevation lakes extends from June through October. Stratification may be persistent, intermittent, or fail to develop largely as a function of depth. Reservoir management may affect stratification by changing the depth; the change occurs largely by removing water from the hypolimnion.

Comparison of Different Averaging Periods

Four different averaging periods are considered in this analysis – summer (July – September), recreation (June - August), stratification (May - September or June - October), and annual. Each has a rationale based on use protection. The summer months have been the basis for assessing attainment of the standard in most lakes subject to Control Regulations; the recreation season corresponds approximately to the months in which swim beaches are monitored; the stratification season has great significance for aquatic life in lakes; and all months are relevant to protection of the drinking water use.

All things being equal, the summer season has advantages in terms of regulatory precedent, availability of historical data, and sampling logistics. Nevertheless, it is important to determine if assessments would be altered substantially by selecting a different averaging period. Assembling a data set is challenging because most lakes are not sampled in all months. The Division, for example, has sampled lakes chiefly in the summer months. Even those lakes sampled throughout the year are rarely sampled with the same frequency in winter and summer.

Twelve lakes have been sampled adequately in all months to support comparisons among the four averaging periods (Table 10). Even for those lakes, the winter months tend to be poorly represented. In addition, there are nine lakes that have been sampled frequently during the ice-free season, and these lakes are included for comparisons among the stratification, recreation, and summer averaging periods.

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arvada	4	3	14	20	22	23	21	25	23	21	17	9
Aurora	10	12	21	24	25	45	48	48	48	44	20	15
Barker					12	17	18	17	14	11		
Barr	6	7	12	12	13	14	14	16	15	16	8	8
Bear Creek	9	8	18	20	35	36	39	38	36	22	18	13
Boulder	1	4	8	15	14	16	16	15	16	15	9	3
Boyd		1	8	10	9	14	10	9	9	10	9	1
Chatfield	8	9	19	22	21	20	39	40	40	19	17	7
Cherry Creek	3	5	12	28	45	47	51	48	48	28	10	1
Dillon	11	11	10		16	36	37	39	33	24	13	4
Granby	4	2	3	1	13	12	15	18	21	15	2	
Grand	4	1	4	1	4	4	7	8	9	6	2	
Green Mountain	6	9	8		10	20	22	20	17	11	9	2
Horse Creek	5	6	4	5	6	7	6	7	7	4	6	6
Horsetooth	1	1	2	6	25	16	18	24	15	16	1	1
Loveland		1	8	10	9	14	9	9	9	10	9	1

Lake	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Milton	6	6	14	13	13	13	16	15	15	14	7	7
Prospect	4	3	4	5	6	6	5	7	4	3	5	4
Quincy	11	12	19	21	24	42	44	43	44	38	19	15
Seaman				15	16	15	14	15	9	10	9	
Standley	20	15	34	35	28	33	33	31	42	42	32	17

Table 10. The number of chlorophyll measurements available in each month for well-sampled lakes. Blank cells indicate no data available for that lake in that month, usually due to safety concerns when ice cover was present.

Uneven sampling across the months creates a statistical problem because an unweighted[36] average of all values within a calendar year is likely to be biased in favor of summer measurements, which comprise a relatively large portion of the data set. The problem can be addressed by computing weighted averages, which compensate for unequal sampling frequency across the months.

Comparisons were made with weighted averages[37] of log-transformed values using Welch's approximate t-test, which is appropriate where variances are assumed to be unequal (Sokal and Rohlf 1995). In general, the summer average is greater than or equal to the recreation average or the stratification average (Table 11). The annual average is sometimes significantly larger than the summer average, but may also be significantly smaller. The stratification average is not significantly different from the recreation average in any of the lakes.

	Summer Compared to:			Annual Compared to:		Stratification Compared to:
Lake	**Annual**	**Stratification**	**Recreation**	**Stratification**	**Recreation**	**Recreation**
Arvada	>	>	ns	ns	ns	ns
Aurora	<	>	>	>	>	ns
Barker		ns	ns			ns
Barr	>	>	ns	ns	ns	ns
Bear Creek	>	>	>	ns	ns	ns
Boulder		ns	>			ns
Boyd		ns	ns			ns
Chatfield	ns	ns	ns	ns	ns	ns
Cherry Creek	ns	>	ns	>	>	ns
Dillon	ns	ns	ns	ns	ns	ns
Granby		ns	ns			ns
Grand		ns	ns			ns
Green Mountain	ns	ns	ns	ns	ns	ns
Horse Creek	ns	ns	ns	ns	ns	ns
Horsetooth		ns	ns			ns

[36] An unweighted average is simply an arithmetic mean where all values are treated equally and without consideration of their spatial or temporal distribution. An unweighted annual average may be biased if samples are taken more frequently during the summer than during the winter.
[37] A weighted average is an arithmetic mean in which an adjustment is made for sampling frequency (inthis case) such that the chlorophyll concentrations from each month are represented equally. The adjustment accounts for the fact that samples may have been weekly during the summer, but only monthly or bi-monthly during the winter.

	Summer Compared to:			Annual Compared to:		Stratification Compared to:
Lake	Annual	Stratification	Recreation	Stratification	Recreation	Recreation
Loveland		ns	ns			>
Milton	>	>	>	ns	ns	ns
Prospect				ns	>	ns
Quincy	ns	>	>	>	>	ns
Seaman		ns	ns			ns
Standley	<	ns	>	>	>	ns

Table 11. Comparison of average chlorophyll concentrations among four averaging periods (annual, summer, stratification, and recreation). Shaded cells indicate where comparisons were not possible due to insufficient data. Cells containing "ns" indicate no significant difference (alpha=0.05; 2-tailed) between the averages. Inequality symbols (">" or "<") are used where the two averages were significantly different, and the symbol indicates which was larger. For example, the "greater than" symbol (>) in the first cell for Arvada Reservoir indicates that the summer average and the annual average were significantly different, and the summer average was larger.

The Division recommends using the summer averaging period – July-September – for criteria development in the general case.[38] There are no strong patterns to suggest a clear advantage for basing assessments on one average or another. Summer and annual averages are not less than stratification or recreation averages, but magnitude alone is not a strong endorsement for an averaging period. On the other hand, the summer averaging period is both practical and defensible in terms of regulatory precedent, the availability of historical data, and the future sustainability of the monitoring program. Of course, the option always exists to propose a site-specific averaging period where there is strong justification, as was the case recently for Standley Lake.

Patterns of Variation in Algal Abundance

The general level of algal abundance in each lake – the trophic condition – is determined largely by the nutrient supply, but algal abundance varies within each averaging period and from year to year. Characterization of the seasonal patterns of variability provides important insights regarding use protection. If the relationship is strong enough, it becomes possible to forecast the distribution of daily concentrations based on a specified target trophic condition. For example, a characterization of variability in summer might make it possible to link the summer average concentration to the frequency of nuisance blooms. The frequency of high chlorophyll concentrations might also support an estimate of the likelihood that pH would exceed the existing standard of 9.0 in a lake that is eutrophic.

The ability to connect daily and seasonal time scales is a tremendous advantage for developing an internally consistent approach to the magnitude component of the chlorophyll criterion. A seasonal average might be justified on the basis of support for a healthy fishery, for example, but it would be valuable to know what the associated risks might be for bloom formation or elevated pH. It allows for fine-tuning the magnitude of the criterion.

Characterization of interannual patterns of variability helps integrate the frequency component of the chlorophyll criterion. This characterization provides the quantitative basis for defining the range of

[38] No change would be proposed for existing site-specific standards, and there would be no prohibition against selecting a different averaging period for a future site-specific value, as long as the data supported the argument.

summer average concentrations that is consistent with the target trophic condition and the threshold beyond which the target condition is no longer being maintained. Colorado has used a return frequency of five years, which is consistent with the typical assessment cycle, to specify how often site-specific nutrient criteria may be exceeded; that practice is applied to the present criteria development effort.

The statistical properties of chlorophyll distributions are evaluated with extensive data sets from a variety of sources, as described below. These data sets are used to separate seasonal and interannual variance, as well as to develop a better understanding of bloom frequency. Separation of variance components is consistent with the target trophic condition approach because it makes it possible to isolate the variability expected during a season.

Variation Within Seasons

The general expectation for chlorophyll concentrations is that the variance of the summer values will increase with the average because the concentrations tend to be log-normally distributed. If the mean-variance relationship is sufficiently strong – and Walker (1985) shows that it can be – it becomes possible to define the variance associated with any average concentration. When the mean and the variance are known, the distribution of individual values can be specified. Given the distribution, bloom frequency (e.g., probability of chlorophyll greater than 30 ug/L) can be predicted in a summer when the average chlorophyll concentration is 20 ug/L, for example.

Chlorophyll data were obtained from a number of different sampling programs, including the Division, United States Geological Survey (USGS), municipalities, and watershed organizations. The period of record extends from 1990 through 2009, with a few more recent samples included for specific purposes. Analysis of seasonal variability included all lakes with at least three summer chlorophyll measurements in one year. Data were excluded from Arvada and Cherry Creek reservoirs because reported concentrations represent the average of two or three replicates.

Standard deviations have been adjusted by the method of Gurland and Tripathi (as presented in Sokal and Rohlf, 1995) to account for the bias introduced by small sample size. Summer average concentrations explain 85 percent of the variance in standard deviation (Figure 17). The relationship is very similar to one derived for Vermont lakes (Walker 1985; $sd = 0.29*avg^{1.21}$, $r^2=0.84$).

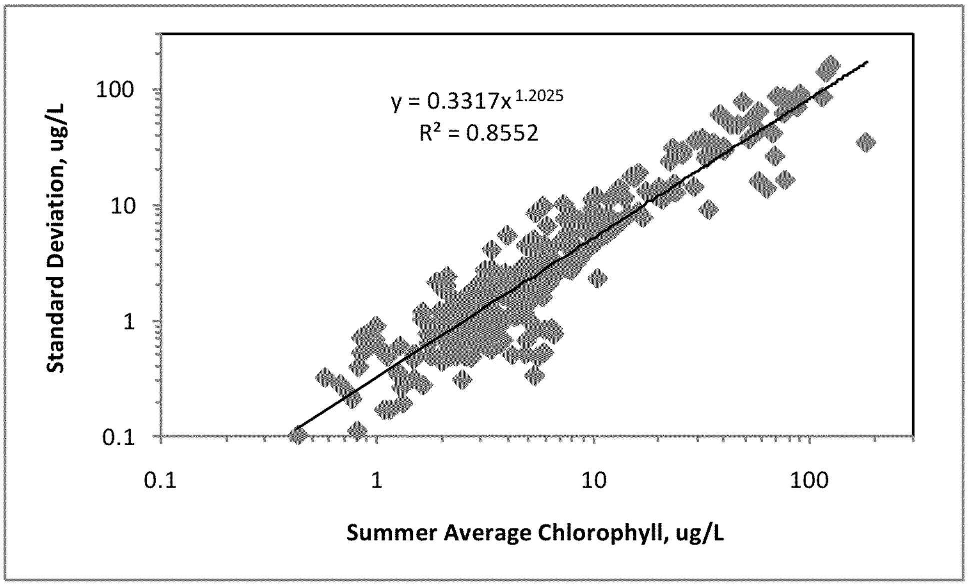

Figure 17. Relationship between the standard deviation (corrected for sample size bias as e xplained in text) and the average of summer chlorophyll concentrations in Colorado lakes. Each point represents one summer for one lake; 283 lake -years of data are included.

Based on the relationship derived for Colorado lakes, the expected frequency of algal blooms can be predicted as a function of the summer average chlorophyll concentration (Figure 18). A threshold concentration of 30 ug/L is usually characterized as a "severe nuisance bloom"[39]. The predicted line is based on Walker's (1985) method and relies on the relationship in Figure 17. Observations can be compared to predictions where sufficient data exist. Data sets are restricted to those summers in which at least six chlorophyll measurements were taken. Although this constraint results in a small number of lake-years, it provides better precision regarding the bloom frequency in each summer.

39 The threshold value was originally defined by Walmsley (1984), and it has been widely cited (e.g., Heiskary and Wilson 2008). Minnesota uses "nuisance" and "severe nuisance" thresholds (20 and 30 ug/L, respectively) for assessing attainment of their water quality narrative standard (MPCA 2009).

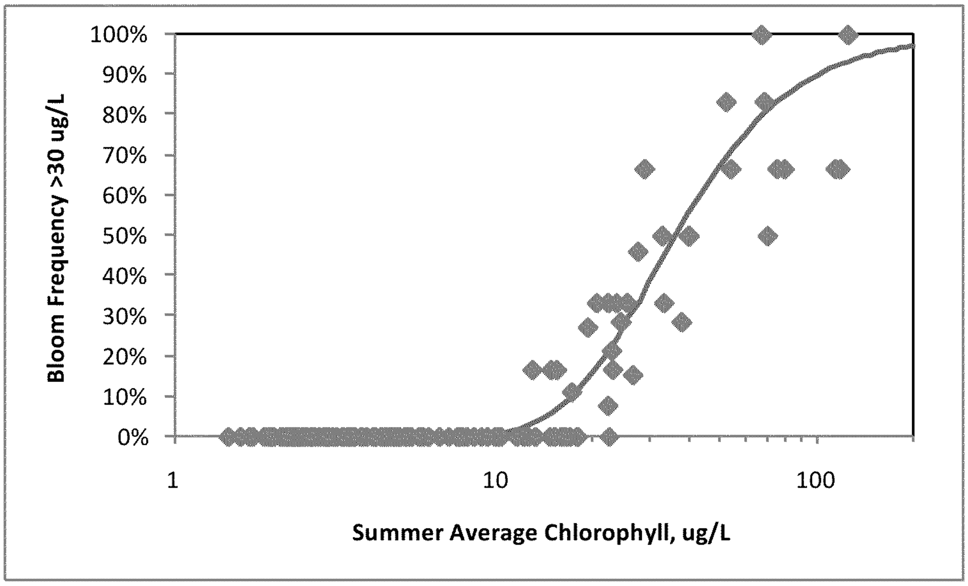

Figure 18. Frequency of algal blooms in excess of 30 ug/L observed in Colorado lakes (symbols) and predicted as a function of summer average chlorophyll concentration (solid line). The basis for the prediction is described in the text. Observations are restricted to summers with at least six measurements of chlorophyll in order to improve precision of frequency estimates.

The same concept is applied to a threshold of 50 ug/L, which the World Health Organization (WHO 2003) has recommended as a "moderate risk level" for recreation. As was true of the 30 ug/L threshold, there is good agreement between observations and predictions. Nuisance blooms do not occur in summers where the average chlorophyll is under 10 ug/L, but become increasingly common when the summer average exceeds 20 ug/L. The WHO risk level is rarely exceeded when summer average chlorophyll concentration is less than 20 ug/L, but are common when the summer average exceeds 30 ug/L. In both cases, there is considerable scatter.

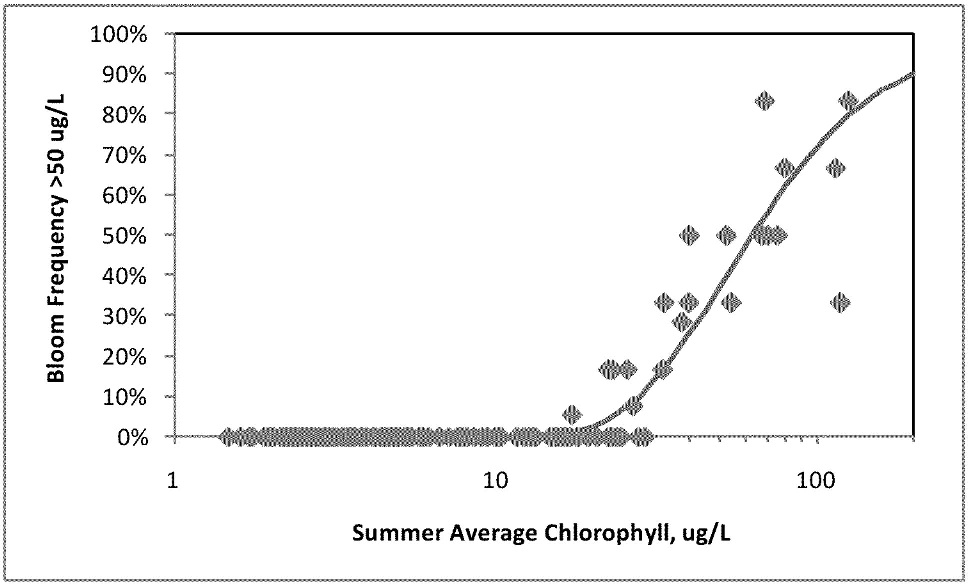

Figure 19. Frequency of algal blooms in excess of 50 ug/L observed in Colorado lakes (symbols) and predicted as a function of summer average chlorophyll concentration (solid line). The basis for the prediction is described in the text. Observations are restricted to summers with at least 6 measurements of chlorophyll in order to improve precision of frequency estimates.

Variation Among Years

There is a strong relationship between the standard deviation and the average for summer chlorophyll concentrations, but the average chlorophyll concentration also varies from year to year. The variation among years is important in two ways – it is central to criteria development in terms of the exceedance frequency for summer averages, and it is important for developing expectations about bloom frequency or pH over the typical assessment period (5 years).

Analysis is restricted to a set of 23 well-studied lakes for which summer averages are available in at least five years. There is a very strong relationship between standard deviation and the long-term summer average chlorophyll concentration (Figure 20), much like the relationship described previously between the standard deviation and each summer average chlorophyll concentration (Figure 17). Standard deviations have been adjusted to account for the bias introduced by small sample size (method of Gurland and Tripathi as presented in Sokal and Rohlf (1995)). The long-term average is the simple average of the available summer averages for each lake.

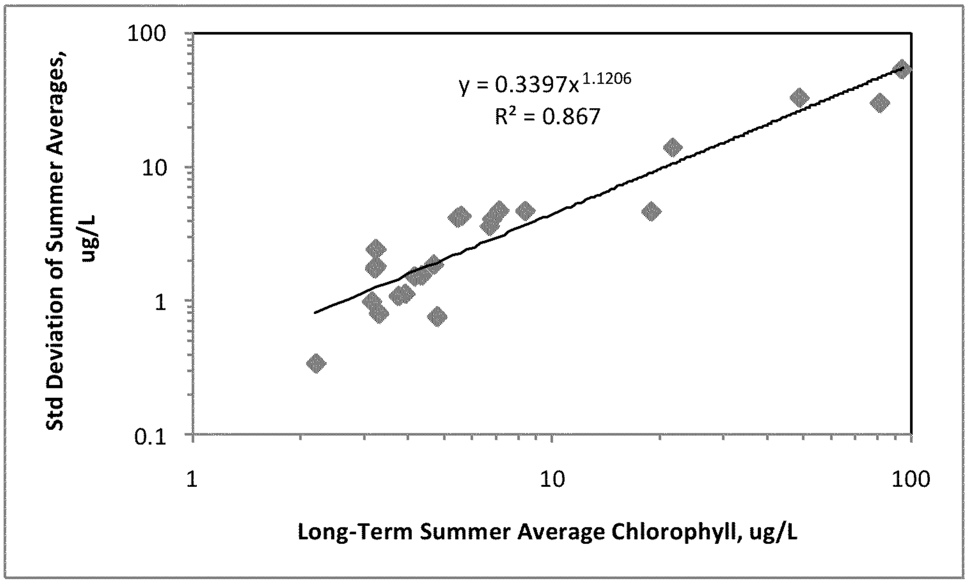

Figure 20. Relationship between the standard deviation, corrected for small sample bias, and the long -term average summer chlorophyll concentration. Each point represents one lake.

Algal Abundance Summary

Algal abundance varies within and among lakes, and an understanding of the patterns of variation is an asset for criteria development. In most Colorado lakes, algal abundance follows seasonal patterns in which abundance tends to be low in spring and high in late summer (or sometimes in winter). The existence of patterns affects the selection of averaging periods.

Four averaging periods – annual, stratification, summer, and recreation – were defined based on rationales related to protection of uses. A comparison of average chlorophyll concentrations among the four averaging periods revealed that summer and annual averages were generally indistinguishable and that both were larger than the stratification and recreation averages, which were indistinguishable from one another. The differences are largely the result of the way the averaging periods were defined relative to the typical seasonal pattern of algal abundance. The stratification and recreation averages were strongly influenced by low algal abundance in the spring.

The Division recommends continued use of the summer average period – July through September. It is practical because it is relatively easy (compared to winter sampling through the ice) to obtain samples, and is a likely time of the year to have data from thirds party sources. Also, it is consistent with long-standing regulatory practices adopted for lakes that are subject to control regulations. In addition, summer is also the time when problems with Cyanobacteria are most likely to occur (see *Algal Abundance and Water Quality Impacts*).

Patterns were also explored concerning variability of chlorophyll concentration within a season and between years. A relationship between the average and the variability of summer chlorophyll measurements will make it possible to estimate the likelihood of risks (e.g., formation of blooms or elevated pH) associated with daily (grab sample) chlorophyll values. A similar relationship for variation among years makes it possible to associate exceedance frequency with the typical summer average. Both relationships are integral to criteria development.

6. Nutrients and Algal Abundance

Nutrients are required for algal growth, and the nutrient supply typically limits the capacity of a lake to support algal abundance[40]. Enriching the nutrient supply to a lake increases its capacity to support algae, and an over-abundance of algae has direct and indirect consequences for protection of uses. Maintaining or restoring use protection depends on understanding and defining the relationship between algal abundance – measured as chlorophyll concentration – and nutrients.

Nutrients *enable* algal growth by establishing a potential for algal abundance, but do not *compel* the algal community to reach that potential. There is a strong relationship between algal abundance and nutrients, but the relationship contains substantial variability not explained by nutrient concentrations alone. Factors other than nutrients can suppress algal abundance, and their action adds variability to the relationship between chlorophyll and nutrients. Context for understanding the variability is provided by assuming that capacity is defined by nutrient concentrations.

When capacity, or potential abundance, is defined based on nutrient concentration alone, actual abundance will always be less than or equal to the potential. Other factors cannot increase the nutrient-based potential, but they can suppress it. Nutrient criteria development can be informed by understanding those factors and any patterns they produce in algal abundance.

Phosphorus and nitrogen are the principal nutrients controlling algal abundance in lakes. Historically, much of the attention was focused on the role of phosphorus, based on the assumption that it was most often the nutrient that determined the capacity of a lake to support algal abundance. For many years, the prevailing scientific view held that phosphorus was almost always the capacity-limiting nutrient in lakes, but support for that position has eroded significantly. There is strong support now for establishment of criteria that include both nitrogen and phosphorus (Conley et al. 2009, Elser et al. 2007, Lewis and Wurtsbaugh 2008, Paerl 2009; but see Schindler et al. 2008 for contrasting view).

Under ideal growth conditions, the potential, or capacity, for algal abundance is about 1 unit of chlorophyll per unit of phosphorus (Reynolds 2006; Chapra 1997; Golterman and de Oude 1991; Riemann et al. 1989). A 1:1 yield would only be possible in a phosphorus-deficient environment because "luxury consumption"[41] would depress the yield. Results from the National Eutrophication Survey (NES) in the 1970s showed that the average yield of chlorophyll was only about 30 percent of that expected on

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[40] Liebig's Law of the Minimum gives rise to the concept of capacity limitation, which simply means that the amount of biomass (algal abundance) that can be sustained is determined by the resource that is in shortest supply compared to demand. In most lakes, phosphorus or nitrogen limits the capacity to support algal abundance. Other factors may limit growth rate, but growth-rate limitation determines the time needed to reach capacity limitation rather than the capacity itself.

[41] Algae are able to store more phosphorus than is needed for immediate metabolic needs. The net effect of this "luxury consumption" is a chlorophyll yield substantially less than would be expected on the basis of the observed phosphorus concentration (up to an order of magnitude according to Reynolds 2006).

the basis of the phosphorus concentration (Hern et al. 1981). Apparently, algal populations do not achieve potential abundance often or sustain it for long. Nevertheless, the 1:1 relationship provides useful context for later comparisons.

Factors Affecting Algal Abundance

The magnitude and relative importance of growth and loss processes cause algal abundance to wax and wane. Changes in abundance can occur very quickly during the summer months when the doubling time for algal cells may be less than a day (cf. Reynolds 2006). When growth processes – nutrients, light, and temperature – dominate, abundance may increase and approach the nutrient-driven capacity.

Suppression of algal abundance below the nutrient-determined potential can occur as a result of environmental factors (e.g., light or temperature) or loss factors. The environment in which the algae live and grow – the mixed layer of a lake – has a variable light regime. At the surface, light intensity varies diurnally, and intensity diminishes with depth. Algae have no capacity to swim against the current and are transported throughout the depth of the mixed layer. Light conditions that may be sufficient near the surface, may be inadequate a few meters below. Net growth may be possible for only part of the daylight hours, with the result that doubling times are slower than would be expected at ambient temperature.

The light regime is also diminished as algal populations expand because the increasing abundance of algal cells – particulate matter – causes light intensity to be attenuated more rapidly with depth. Shading also increases when non-algal particulate matter increases. Hoyer and Jones (1983) showed that increasing the concentration of inorganic suspended solids (ISS) decreases chlorophyll per unit phosphorus (i.e., a lower slope for the chlorophyll-phosphorus relationship). High ISS concentration causes shading that is in addition to that caused by algal abundance.

In addition to the factors that sustain algal growth, there are a number of significant loss factors that can slow the net growth rate or reduce algal abundance. Important loss mechanisms include settling, washout, and grazing; parasitism and disease may also play a role. Algal cells tend to be more dense than the surrounding medium and thus will sink, albeit slowly. Sinking can be offset by turbulence, but some cells inevitably sink out of the mixed layer and no longer contribute to abundance or growth. Algal abundance also is reduced as water moves into a lake, diluting algal biomass locally and displacing some biomass into the outflow.

Grazers (herbivorous zooplankton) have considerable capacity to reduce algal abundance, especially where the algae are suitable in size and abundance for sustaining populations of filter-feeding zooplankton (Reynolds 2006). In general, zooplankton communities dominated by large herbivores, like the cladoceran *Daphnia*, are more effective at reducing algal abundance than are communities dominated by small herbivores (Mazumder and Havens 1998).

The following four figures build a conceptual view of the relationship between nutrients and chlorophyll. It is very simplistic and intended solely to convey an understanding of the dynamic interactions that occur in lakes. The first figure assumes that phosphorus concentration is the only factor controlling the abundance of algae (Figure 21); the observed abundance equals the capacity of the lake to support algae. Of course, it is unrealistic to assume that algae would be able to reach the capacity for any level of phosphorus even for a short time, even if the nitrogen supply was always in excess of requirements.

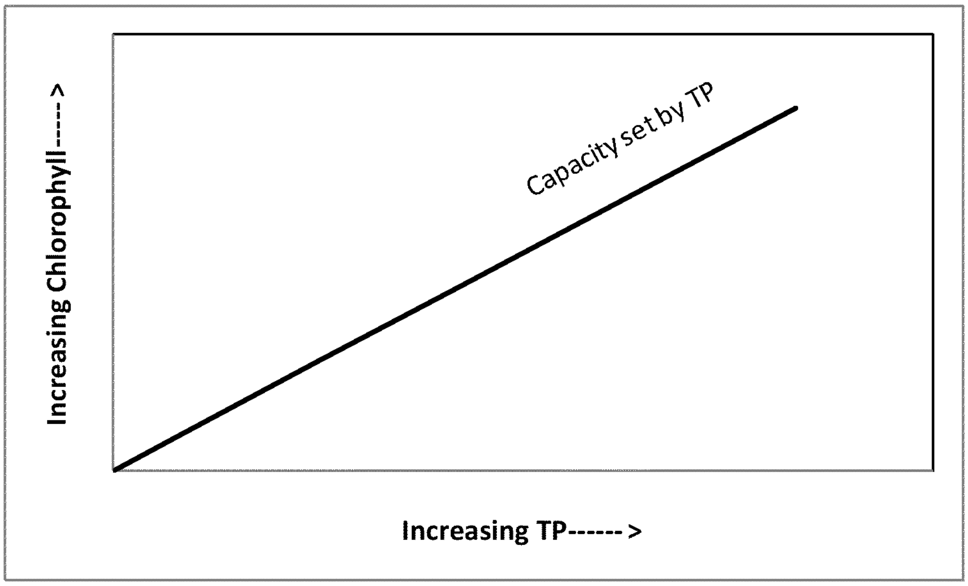

Figure 21. Conceptual model of algal abundance driven solely by the availability of phosphorus (TP). Chlorophyll concentration is shown increasing one unit for each unit of increase in phosphorus.

At some point, algal abundance reaches a level where the physical presence of so many particles (i.e., algal cells) blocks enough light that further increase in abundance is not possible, even when phosphorus and nitrogen are present in excess of requirements. The capacity expected on the basis of the phosphorus supply is superseded by light limitation (Figure 22). The figure treats light as if it were constant across the spectrum of phosphorus conditions. Of course, it varies on daily and seasonal cycles, and may be altered at any time by weather conditions and other factors. In other words, the notion of light limitation is only constant in theory.

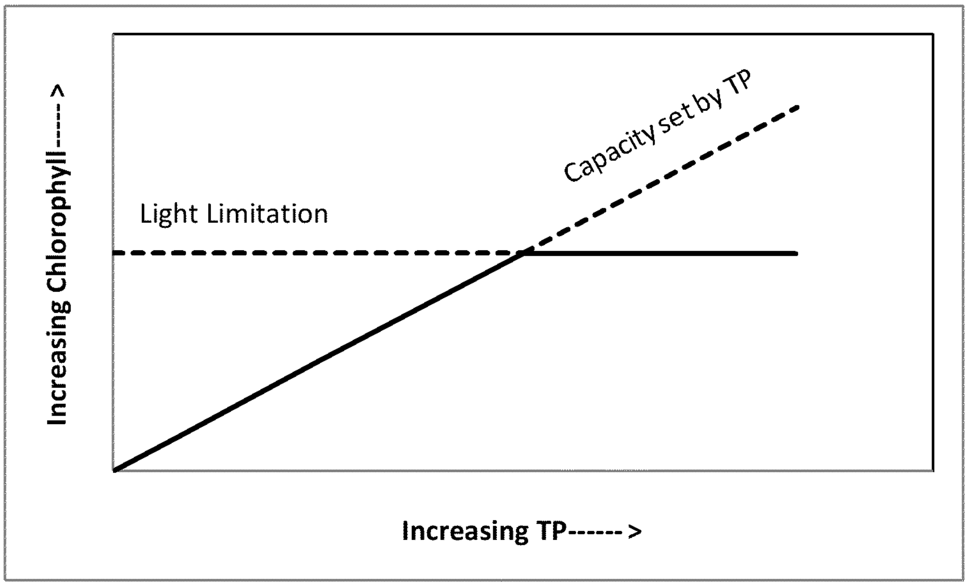

Figure 22. Conceptual model where light limitation suppresses algal abundance below the capacity expected on the basis of the phosphorus concentration. The solid line shows chlorophyll concentration as a function of phosphorus concentration. The dashed lines show how each factor – phosphorus and light – would affect capacity. Adapted from Reynolds (1992).

The two preceding figures have assumed that nitrogen was always sufficiently abundance that it did not control algal abundance. In many situations, this will not be true. For the conceptual model, a scenario is constructed where nitrogen concentration is low and constant across all phosphorus conditions. In addition, the capacity set by nitrogen is low enough that light is not limiting (Figure 23).

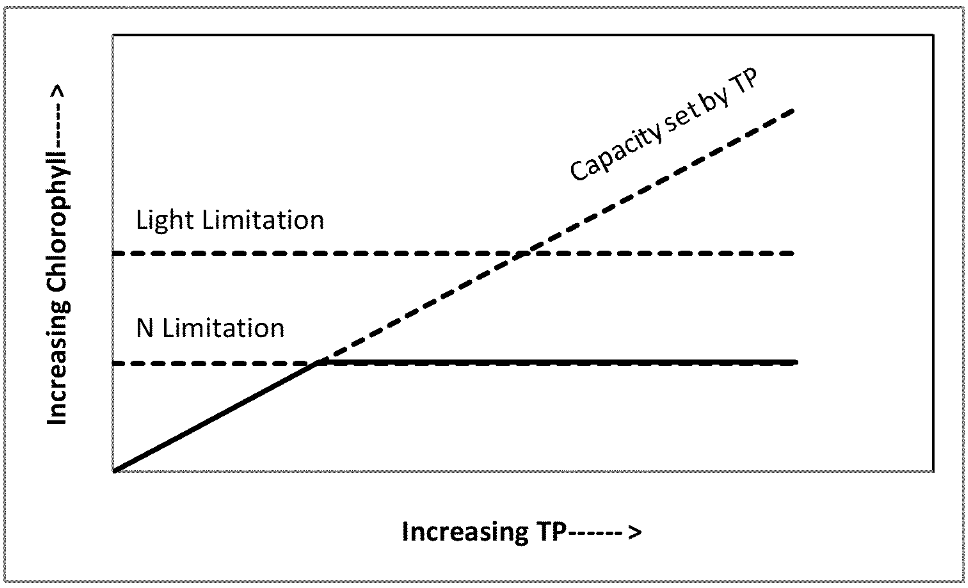

Figure 23. Conceptual model where nitrogen limitation suppresses algal abundance below the capacity expected on the basis of the phosphorus concentration and light. The solid line shows chlorophyll concentration as a function of phosphorus concentration. The dashed lines show how each factor – phosphorus, light, and nitrogen – would affect capacity. Adapted from Reynolds (1992).

The three preceding figures have dealt with the capacity of a lake to support algal abundance as determined by nutrients and light, which are growth factors. In natural settings, abundance is usually kept below capacity by the operation of loss factors. To illustrate the role of the loss factors, one scenario is developed in which grazing (or washout or settling) suppresses abundance ten percent below capacity (Figure 24), as defined in each of the three preceding figures. The loss scenario is applied to each of the three capacity scenarios, all at a fixed phosphorus concentration, to show how the interaction of growth and loss factors can lead to different outcomes.

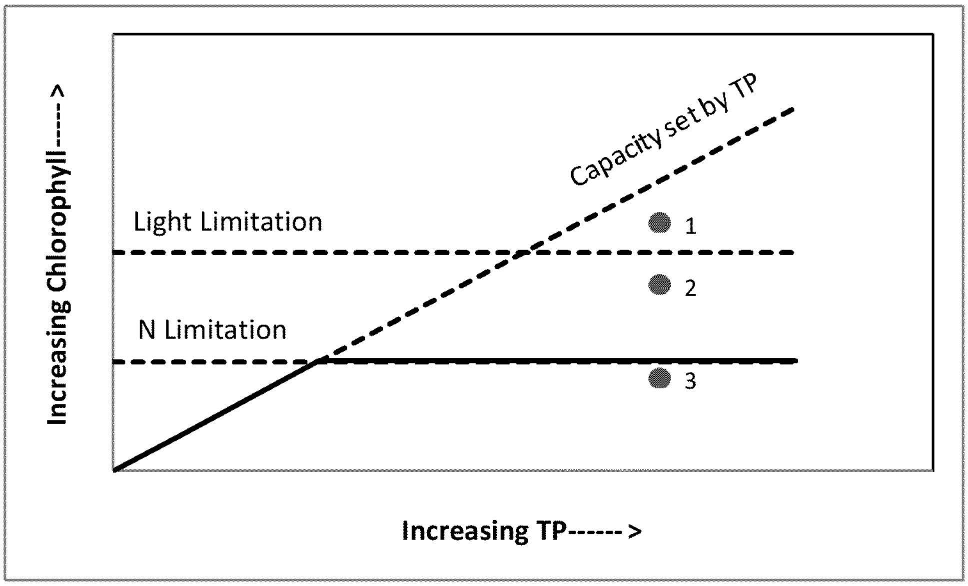

Figure 24. Conceptual model as described in Figure 23, with addition of three solid circles indicating a 10% reduction in algal abundance below the capacity determined by phosphorus (1), light (2), or nitrogen (3).

Observed Relationships between Nutrients and Algal Abundance

Chlorophyll increases almost linearly with phosphorus over a broad range of phosphorus concentrations. At very low and very high phosphorus concentrations, the nature of the relationship changes, giving rise to an "S"-shaped, or sigmoid, pattern that has been described in a number of studies (McCauley et al. 1989, Watson et al. 1992, and Chow-Fraser et al. 1994; see also Prairie et al. 1989 for a related analysis with a different statistical approach). A lessening of the chlorophyll response to phosphorus at the high end of phosphorus concentrations has been attributed to an increasing role for nitrogen (Chow-Fraser et al. 1994).

There is also a strong positive correlation between nitrogen and phosphorus in lakes. Across a broad spectrum of nutrient enrichment in lakes, nitrogen and phosphorus tend to increase together, although nitrogen increases at a slower rate. The rate matters because nutrient enrichment tends to lead to a scarcity of nitrogen relative to the phosphorus concentration. In other words, the ratio of nitrogen to phosphorus, which is often used as an indicator of nutrient deficiency[42], declines across the range of phosphorus concentrations.

Available Data

Nutrient data have been collected from Colorado lakes since the 1930s, but few comprehensive studies were undertaken before the 1980s.[43] For criteria development, the data record begins with samples collected in 1990 and extends into 2010 in some cases. In that time, 4,867 chlorophyll measurements were recorded from 162 lakes, 4,973 measurements of total phosphorus from 165 lakes, and 1,923 measurement of total nitrogen from 102 lakes. The lakes represent a broad cross-section of those lakes for which the numeric criteria are intended to apply; there are about 330 lakes with surface area greater than 25 acres.

Chlorophyll-Phosphorus Relationships

Summer data from 154 Colorado lakes show that algal abundance increases with increasing phosphorus concentration over a broad range of values (Figure 25). Linear regression with natural-log transformed (ln-transformed) values explains about half of the variance in chlorophyll concentration on the basis of the phosphorus concentration. In general, the upper bound for chlorophyll concentration is consistent with expectations based on phosphorus concentration (i.e., potential yield is approximately 1 ug chlorophyll per ug total phosphorus). A few points lie above the phosphorus-defined capacity, and these are probably attributable to measurement precision or to uneven spatial distribution of algae (e.g., clumping due to hydrodynamic factors). At the upper end of observed phosphorus concentrations, the likelihood of reaching (phosphorus-determined) capacity appears to be reduced.

[42] For discussion of nutrient ratios and ecological implications, see Sterner and Elser (2002). Ratios can be calculated in molar or mass units. Mass ratios are more useful when dealing with concentrations. The conversion to mass from molar is based on 14 g/mole for nitrogen and 31 g/mole for phosphorus.

[43] Dr. Robert Pennak initiated limnological studies in Colorado shortly after he arrived at the University of Colorado in the mid-1930s. The work continued until his retirement in 1974. His nutrient analyses were generally restricted to soluble reactive phosphorus and nitrate-nitrogen. In the early 1980s, comprehensive studies were initiated in three reservoirs – Dillon, Chatfield, and Cherry Creek – that later became subject to control regulations. Bear Creek Reservoir joined their ranks in 1990, and later several municipalities began long-term monitoring programs.

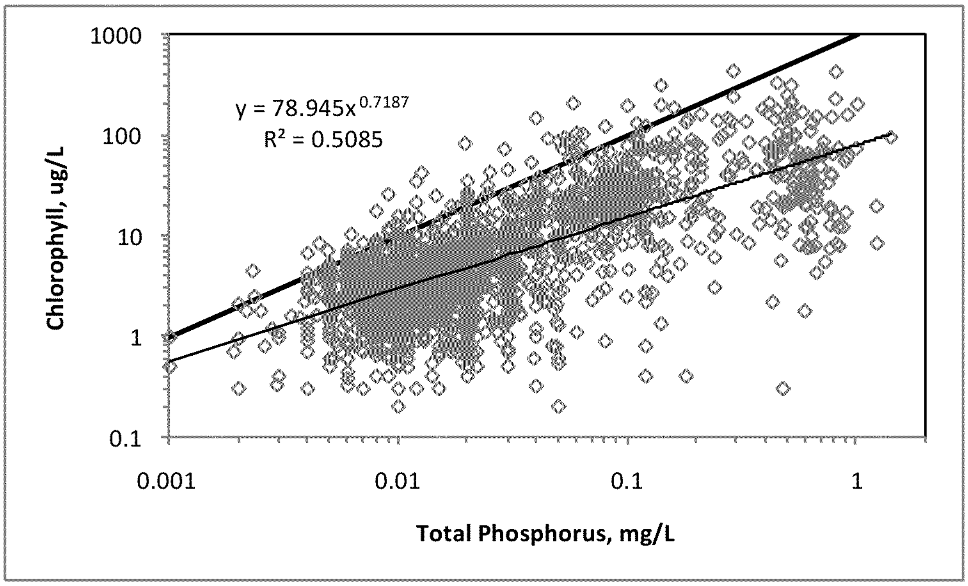

Figure 25. Relationship between chlorophyll and phosphorus concentrations in grab samples taken from Colorado lakes during the summer (July - September). Data are shown from 154 lakes; the number of measurements per lake is variable. The thick, solid line indicates where algal abundance has reached the capacity defined by the corresponding phosphorus concentration. A power function is fit to the data (thin, solid line), and the equation is inset at the upper left of the fi gure. A few points with phosphorus concentrations less than 0.001 mg/L were omitted to red uce scale compression.

A similar pattern of chlorophyll yield is seen in data from the recent National Lakes Assessment (NLA), which sampled more than a thousand lakes in 2007 (Figure 26), and the National Eutrophication Survey (NES), which sampled 757 lakes throughout the US in the 1970s (Figure 4 in Hern et al. 1981). All three data sets show a strong relationship between chlorophyll and phosphorus in which potential yield can be reached over a broad range of phosphorus concentrations. At very high phosphorus concentrations – greater than about 0.1 mg/L – variance appears to increase and the potential chlorophyll yield is rarely reached.

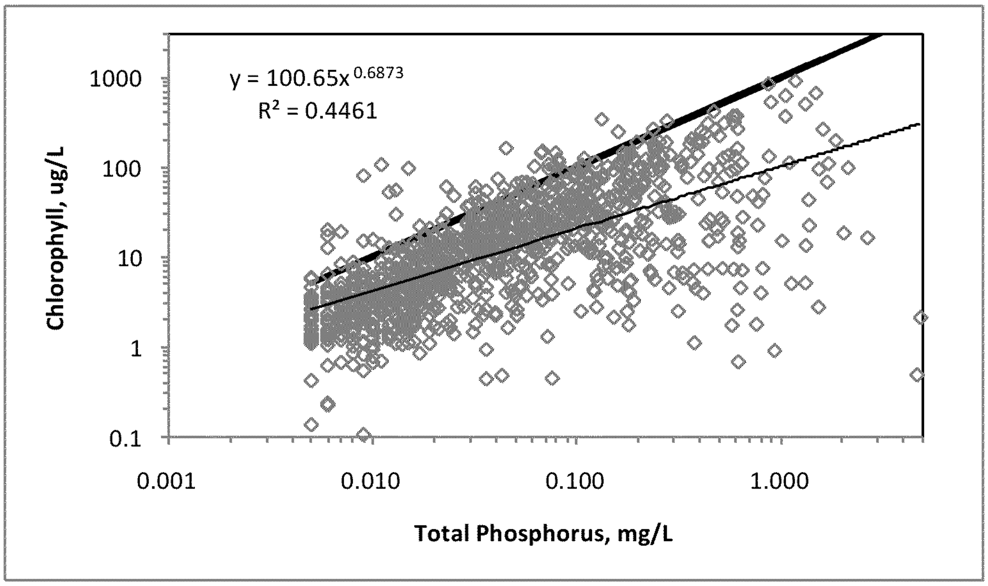

Figure 26. Relationship between chlorophyll and phosphorus concentrations in grab samples taken from the National Lake Assessment during 2007 (June - October). Data are shown from more than 1000 lakes most of which were sampled once. The thick, solid line indicates where algal abundance has reached the capacity defined by the corresponding phosphorus concentration. A power function is fit to the data (thin, solid line), and the equation is inset at the upper left of the fi gure. Points with phosphorus concentrations less than or equal to the detection limit (0.004 mg/L) were omitted.

The regression lines obtained for Colorado and NLA data sets were compared by adding a "dummy" variable (also called an indicator variable) to the analysis (Kleinbaum and Kupper 1978). The dummy variable simply identifies the data source – Colorado or NLA – and makes it possible to compare the two regression equations in one regression model. The advantage of a single model is that it uses all available data and produces a single equation that is applicable if there are no significant differences in slope or intercept for the two data sources.

Comparison of the Colorado and NLA data sets revealed no significant difference for the slopes, but a significant difference (p=0.000) for the intercepts (Figure 27). Thus, across the entire range of phosphorus concentrations, the incremental response of algal abundance is the same. Both sets also conform similarly to the upper bound, indicating similar potential yield of chlorophyll. The sets differ in terms of the range of phosphorus values; the NLA set is truncated at the lower end and includes much higher concentrations (4.0 mg/L vs. 1.0 mg/L for Colorado).

Regression Analysis: LN Chl (ug/L) versus LN TP (mg/L), Dummy, Interaction

```
The regression equation is
LNChl = 4.61 + 0.687 LN TP mg + 4.71 Dummy + 0.0296 Interact 2


2937 cases used, 11 cases contain missing values


Predictor       Coef  SE Coef      T      P
Constant     4.61168  0.07417  62.18  0.000
LN TP mg     0.68735  0.02119  32.44  0.000
Dummy         4.7105   0.2002  23.53  0.000
Interact 2   0.02960  0.02742   1.08  0.280


S = 0.983069   R-Sq = 51.2%   R-Sq(adj) = 51.2%


Analysis of Variance

Source            DF       SS      MS        F      P
Regression         3  2977.65  992.55  1027.03  0.000
Residual Error  2933  2834.52    0.97
Total           2936  5812.17
```

Figure 27. Results of regression analysis to compare equations defining chlorophyll as a function of total phosphorus for data from Colorado and NLA lakes. Analysis was performed with Minitab Regression using ln -transformed values for chlorophyll (LNChl) and total phosphorus (LNTP). A dummy variable was included with the value set to 1 for Colorado data and 0 for NLA data. The "Dummy" term in the analysis shows that there is a significant difference in the intercepts. The "Interaction" term shows that there is no significant difference for the slopes.

Chlorophyll-Nitrogen Relationships

A similar analysis was undertaken to compare equations relating chlorophyll to total nitrogen. Linear regression with ln-transformed values from Colorado lakes explains about half of the variance in chlorophyll concentration on the basis of the nitrogen concentration (Figure 28). In general, the upper bound for chlorophyll concentration is consistent with expectations based on nitrogen concentration (i.e., the ratio of chlorophyll to nitrogen is approximately 0.11:1; Reynolds 2006). In general, the capacity, in terms of nitrogen concentration, is not approached until nitrogen concentrations are very high. This appears to coincide with the total phosphorus concentration above which actual algal abundance consistently falls below capacity.

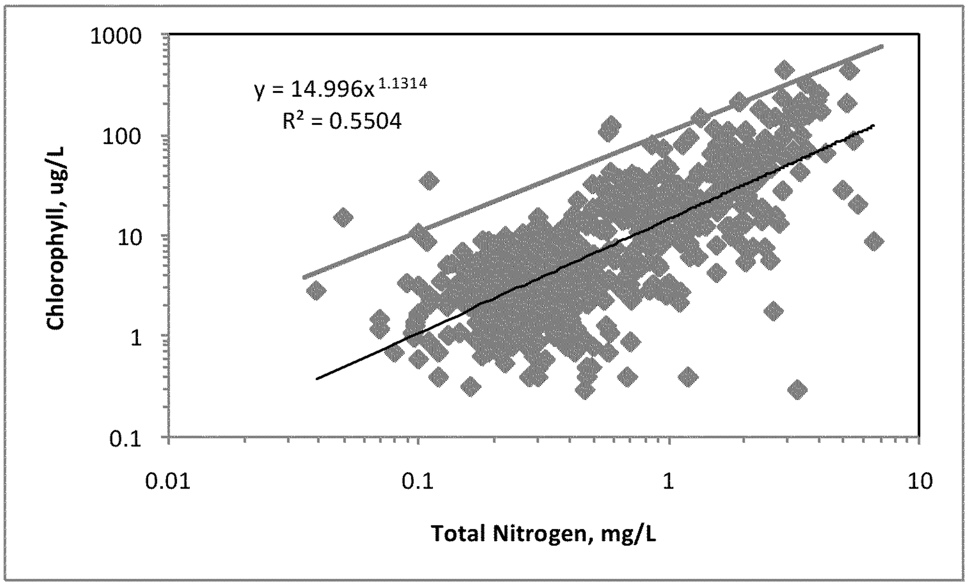

Figure 28. Relationship between chlorophyll and nitrogen concentrations in grab samples taken from Colorado lakes during the summer (July - September). Data are shown from 91 lakes; the number of measurements per lake is variable. The thick, solid line indicates where algal abundance has reached the capacity defined by the corresponding nitrogen concentration. A power function is fit to the data (thin, solid line), and the equation is inset at the upper left of the figure.

The relationship between chlorophyll and nitrogen in the NLA lakes (Figure 29) is similar in some respects to the Colorado data. It is rare for chlorophyll to approach the nitrogen-driven potential when nitrogen concentrations are below about 1.0 mg/L. However, at very high concentrations – greater than about 5.0 mg/L – chlorophyll is again below the potential; there are no nitrogen values in this range in the Colorado data.

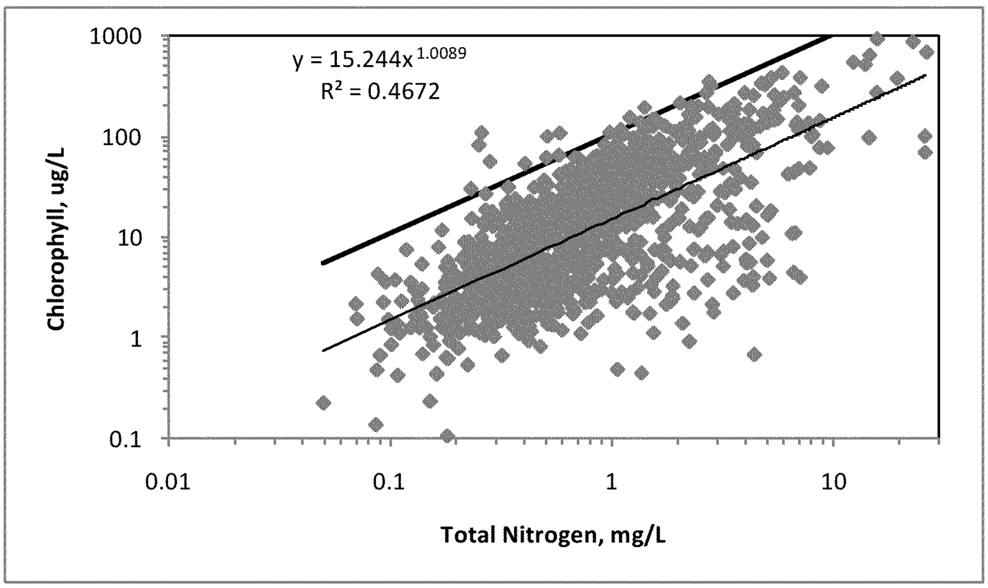

Figure 29. Relationship between chlorophyll and nitrogen concentrations in grab samples taken from the National Lake Assessment during 2007 (June - October). Data are shown from more than 1,000 lakes most of which were sampled once. The thick, solid line indicates where algal abundance has reached the capacity defined by the corresponding nitrogen concentration. A power function is fit to the data (thin, solid line), and the equation is inset at the upper left of the figure.

Comparison of the Colorado and NLA data sets revealed significant differences for the slopes and the intercepts of the relationships between chlorophyll and nitrogen (Figure 30). Although the lines are not coincident, they intersect at a total nitrogen concentration of about 1.0 mg/L and yield very similar values (+/-10 percent) over a broad range – 0.5 to 2.5 mg/L. It seems likely that at very high nitrogen levels, not found in the Colorado data set, chlorophyll falls below the potential due to self-shading. The effect, from a statistical perspective, is to diminish the slope for the NLA data.

Regression Analysis: LN Chl (ug/L) versus LN TN (mg/L), Dummy, Interaction

```
The regression equation is
LNChl = 2.72 + 1.01 LN TN mg - 0.0164 Dummy + 0.122 Interact 2


Predictor        Coef  SE Coef      T      P
Constant      2.72417  0.03160  86.21  0.000
LN TN mg      1.00889  0.03086  32.69  0.000
Dummy        -0.01636  0.05528  -0.30  0.767
Interact 2    0.12247  0.04951   2.47  0.013


S = 0.998334   R-Sq = 51.8%   R-Sq(adj) = 51.8%


Analysis of Variance

Source            DF       SS      MS       F      P
Regression         3  2054.61  684.87  687.16  0.000
Residual Error  1916  1909.62    1.00
Total           1919  3964.23
```

Figure 30. Results of regression analysis to compare equations defining chlorophyll as a function of total nitrogen for data from Colorado and NLA lakes. Analysis was performed with Minitab Regression using ln-transformed values for chlorophyll (LNChl) and total nitrogen (LNTN). A dummy variable was included with the value set to 1 for Colorado data and 0 for NLA data. The "Dummy" term in the analysis shows that there is a significant difference in the inte rcepts. The "Interaction" term shows that there also is a significant difference for the slopes.

Nutrient Limitation and Inferences about Nutrient Deficiency

Nutrient limitation[44] has been tested experimentally in a number of Colorado lakes (Morris and Lewis 1988, Lewis et al. 1984, Lewis et al. 2007, WQCD studies of Chatfield and Cherry Creek reservoirs, Gardner et al. 2008). Results show some cases of nitrogen-limitation, some cases with some combination of nitrogen and phosphorus very closely balanced, and others of phosphorus-limitation alone. It is likely that nutrients are closely balanced in many lakes, so that an addition of both nitrogen and phosphorus is likely to produce a much greater response than addition of either one (see Elser et al. 2007 for a broader treatment of this subject).

Studies of nutrient limitation in nearby states also support the argument that nitrogen limitation is a possibility for Colorado lakes at all elevations. In Wyoming, a recent study of shallow mountain lakes showed that phytoplankton responded to nitrogen and to nitrogen plus phosphorus, but not to

[44] Herein, nutrient limitation is restricted to experimental demonstration that algal abundance increases in response to nutrient addition.

phosphorus alone (Nydick et al. 2004). Similar results (i.e., principally nitrogen-limitation or co-limitation) were reported in a study of Kansas reservoirs, all of which drain largely agricultural watersheds (Dzialowski et al. 2005).

Inferences about nutrient limitation are often made on the basis of nutrient ratios. Comparison of ambient ratios of total nitrogen to total phosphorus (TN:TP) with experimental documentation of nutrient limitation has produced some generalizations for interpreting ratios. Mass ratios in the range of 5 to 10 form a boundary below which nitrogen deficiency is expected, and mass ratios in the range of 17 to 23 form a boundary above which phosphorus deficiency is expected (Table 12).

Upper Boundary of N-deficiency	Lower Boundary of P-deficiency	Source
9:1	22.6:1	Guildford and Hecky 2000
10:1	17:1	Sakamoto (cited in Smith 1982)
5:1	20:1	Thomann and Mueller 1987
5:1	20:1	Downing and McCauley 1994

Table 12. Boundaries for nutrient deficiency in lakes defined on the basis of mass ratios of nitrogen to phosphorus (TN:TP). Nitrogen deficiency is expected when TN:TP falls below the value in the first column; phosphorus deficiency is expected when TN:TP exceeds the value in the second column.

The Division chose the boundaries proposed by Downing and McCauley (1994) for the purpose of identifying likely nutrient deficiency. Phosphorus is deficient if the ratio exceeds 20:1 and nitrogen is deficient if the ratio is less than 5:1. Nutrient limitation can be inferred where ratios indicate deficiency.

The relationships between chlorophyll and phosphorus and between chlorophyll and nitrogen suggest that concentrations of the two nutrients tend to co-vary. That is, high phosphorus levels are very likely to be accompanied by high nitrogen levels, and low phosphorus levels are very likely to be accompanied by low nitrogen levels. The underlying relationship is strong, and it reveals an important pattern from which an inference can be drawn regarding nutrient deficiency in Colorado lakes (Figure 31).

Most Colorado lakes with low phosphorus concentrations (less than about 0.010 mg/L) are likely to be phosphorus deficient. Those with high phosphorus concentrations (greater than about 0.200 mg/L) are likely to be nitrogen deficient. Many lakes fall between the boundaries where nutrient supplies are more closely balanced. The shift in expectations for nutrient deficiency with increasing TP concentration is probably attributable to a change in the dominant source(s) of nutrients. Point sources tend to have very low ratios; a typical value for domestic wastewater influent is about 3:1 and for effluent about 5:1.[45] Runoff from feedlots and pasturelands also has very low ratios (Arbuckle and Downing 2001; Sterner and Elser 2002).

[45] Taken from “commonly accepted BOD/N/P weight ratio*s+” provided in Lin (2007).

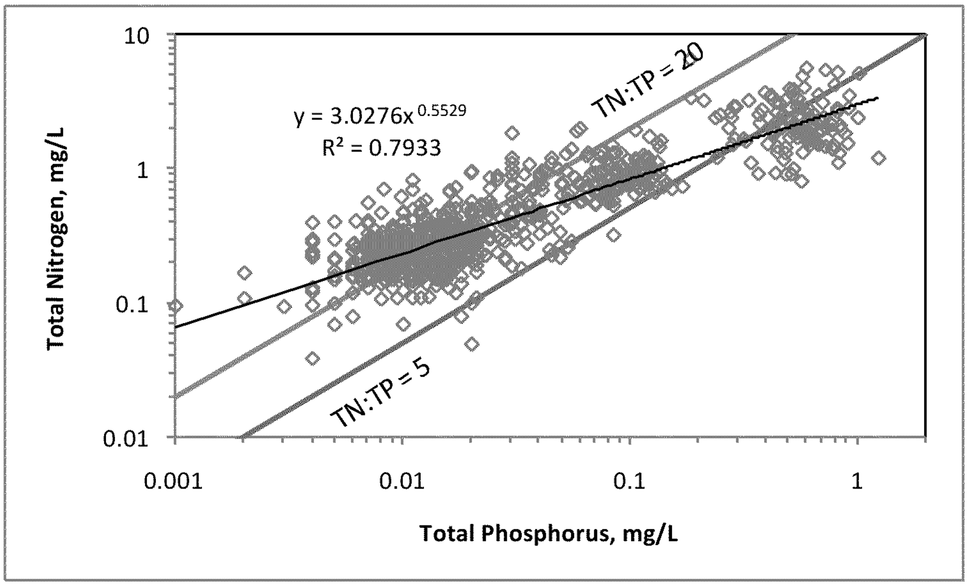

Figure 31. Relationship between nitrogen and phosphorus concentrations in grab samples taken from Colorado lakes during the summer (July - September). Data are shown from 95 lakes; the number of measurements per lake is variable. The t rend line (thin, solid) shows a strong relationship between ln -transformed concentrations. The upper solid line (green) shows the total nitrogen concentration expected when the TN:TP ratio is 20:1; points above this line indicate phosphorus deficiency. The lower solid line (red) shows the nitrogen concentration expected when the TN:TP ratio is 5:1; points below this line indicate nitrogen deficiency.

The relationship for NLA data is very similar, but displaced slightly such that the low phosphorus boundary is about 0.020 mg/L and the high boundary is about 0.500 mg/L (Figure 32). Both sets have many lakes that fall between the lines, suggesting that nitrogen and phosphorus concentrations frequently are more closely balanced.

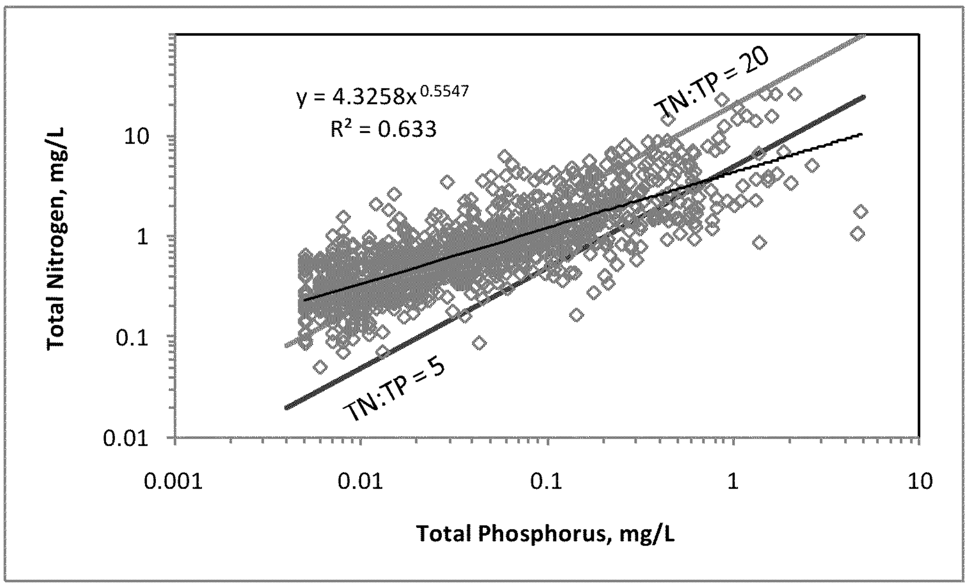

Figure 32. Relationship between total nitrogen and total phosphorus in grab samples from the 2007 NLA. The thin black line is the line of best fit to the data. The upper solid line (green) shows the total nitrogen concentration expected when the

TN:TP ratio is 20:1; points above this line indicate phosphorus deficiency. The lower solid line (red) shows the nitrogen concentration expected when the TN:TP ratio is 5:1; points below this line indicate nitrogen deficiency.

Comparison of the Colorado and NLA equations shows that the slopes are almost identical, but the intercepts are different (Figure 33). The point of the comparison is not to suggest that changes in phosphorus "cause" changes in nitrogen, but it is a convenient way to show that the strong positive correlation between phosphorus and nitrogen provides a rational basis for understanding broad patterns in nutrient-chlorophyll relationships in Colorado lakes.

Regression Analysis: LN TN (mg/L) versus LN TP (mg/L), Dummy, Interaction

```
The regression equation is
LN TN mg = 1.46 + 0.555 LN TP mg - 0.357 Dummy - 0.0018 Interact 2


Predictor        Coef  SE Coef      T      P
Constant      1.46459  0.03911  37.45  0.000
LN TP mg      0.55470  0.01117  49.65  0.000
Dummy        -0.35683  0.05983  -5.96  0.000
Interact 2   -0.00177  0.01643  -0.11  0.914


S = 0.518354   R-Sq = 71.7%   R-Sq(adj) = 71.7%


Analysis of Variance

Source            DF       SS      MS        F      P
Regression         3  1348.88  449.63  1673.40  0.000
Residual Error  1979   531.74    0.27
Total           1982  1880.62
```

Figure 33. Results of regression analysis to compare equations defining total nitrogen as a function of total phosphorus for data from Colorado and NLA lakes. Analysis was performed with Minitab Regression using ln - transformed values for total nitrogen (LNTP) and total phosphorus (LNTP). A dummy variable was included with the value set to 1 for Colorado data and 0 for NLA data. The "Dummy" term in the analysis shows that there is a significant difference in the intercepts. The "Interaction" term shows that there is no significant diffe rence for the slopes.

Hidden behind the broad generalizations about nutrient limitation and deficiency are seasonal shifts, as has been observed in Colorado lakes (Morris and Lewis 1988). In Dillon Reservoir, for example, the limiting nutrient may shift from phosphorus to nitrogen late in stratification, and back to phosphorus just before turnover. Not surprisingly, the onset of nitrogen limitation coincided with depletion of nitrate in the mixed layer.

Depletion of nitrate in the mixed layer in late summer appears to be relatively common in Colorado lakes. This pattern is usually indicative of nitrogen deficiency, if not limitation. Data from seventeen lakes with strong data sets and sensitive analytical methods were examined for seasonal patterns in nitrate concentration. Most of the lakes showed strong seasonal patterns with a distinct minimum in summer. Of those with strong seasonal patterns[46], several showed exhaustion of nitrate in some or all years. Bear Creek Reservoir (Figure 34) and Barr Lake (Figure 35) are shown as examples.

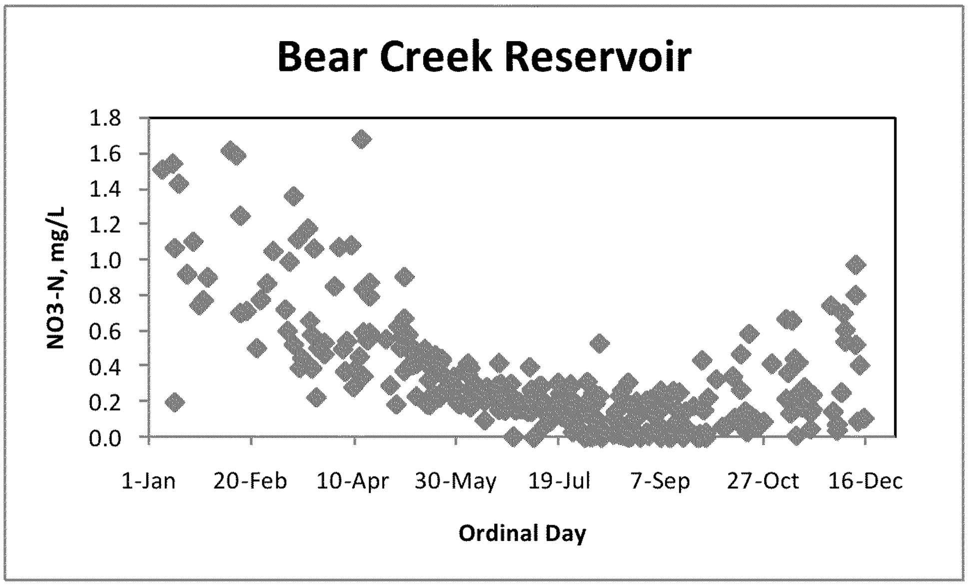

Figure 34. Seasonal pattern of nitrate-nitrogen concentration in Bear Creek Reservoir. Data from several years are combined by plotting against day of year (ordinal day) to highlight seasonal pattern.

Dillon Reservoir also shows a very strong seasonal pattern in nitrate concentration, but the pattern has changed over time. In the early 1980s, exhaustion of nitrate was observed (Lewis et al. 1984), and that pattern persisted through much of the 1990s (Figure 36). Subsequently, however, the seasonal pattern is less pronounced and nitrate is not exhausted (Figure 37), apparently due to increased loading from anthropogenic sources (Kaushal et al. 2006).

[46] Of 17 lakes with suitable data, Barr, Milton, Horse Creek, Prospect, Horsetooth, Bear Creek, Grand, Green Mountain, Dillon, Barker, Standley, Horseshoe, Boyd, and Seaman showed strong patterns. Loveland, Boulder, and Cherry Creek did not show clear seasonal patterns.

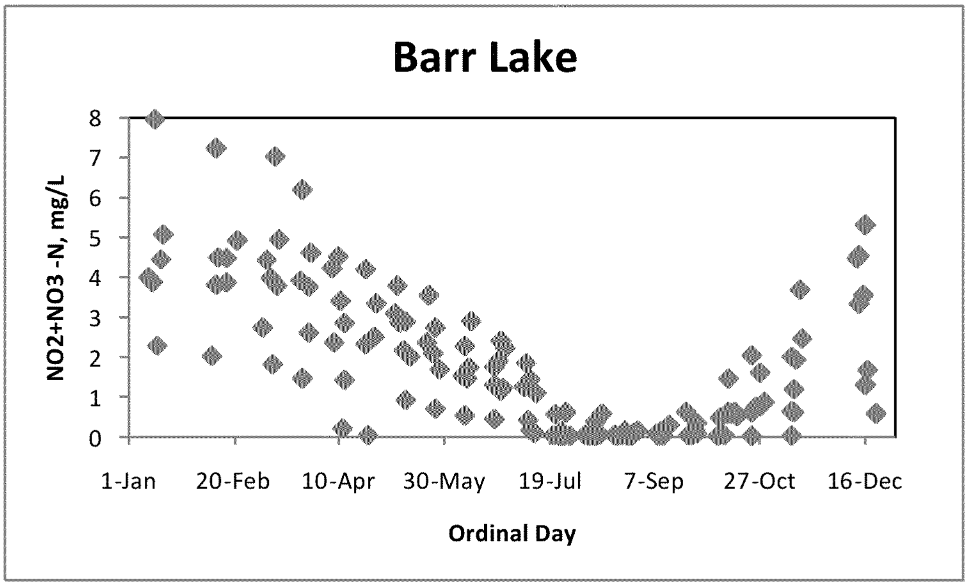

Figure 35. Seasonal pattern of nitrate+nitrite-nitrogen concentration in Barr Lake. Data from several years are combined by plotting against day of year (ordinal day) to highlight seasonal pattern.

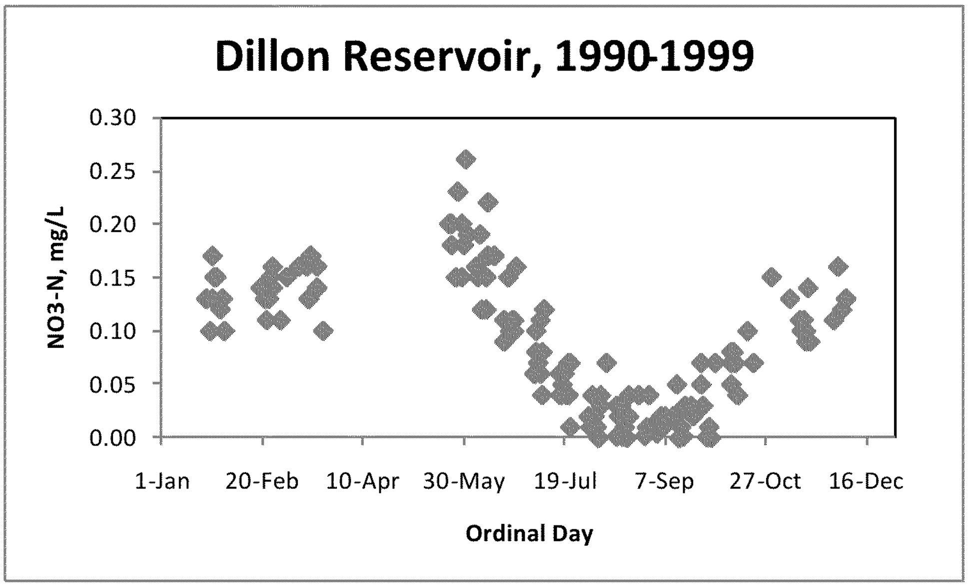

Figure 36. Seasonal pattern of nitrate-nitrogen concentration in the mixed layer of Dillon Reservoir. Data from 1990-1999 are combined by plotting against day of year (ordinal day) to highlight seasonal pattern.

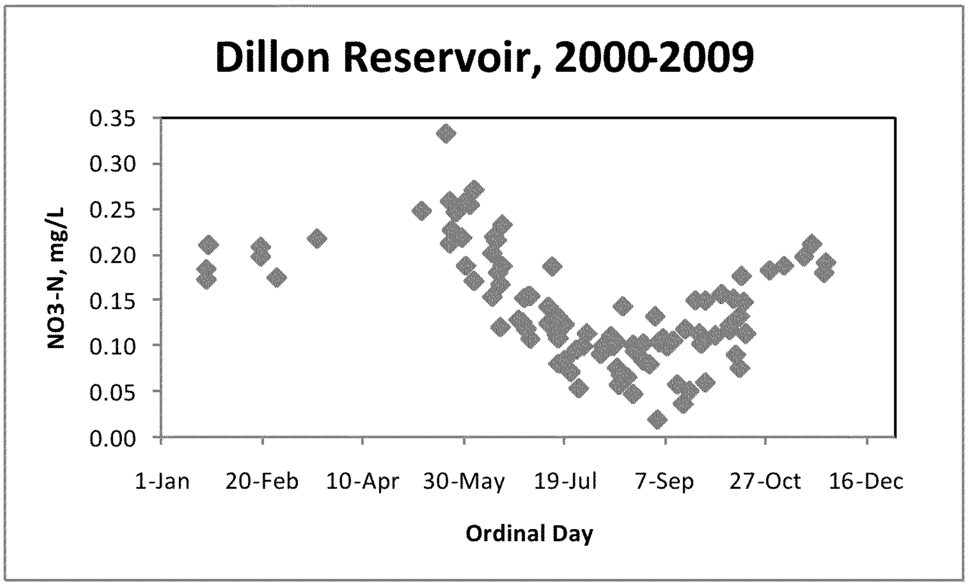

Figure 37. Seasonal pattern of nitrate-nitrogen concentration in the mixed layer of Dillon Reservoir. Data from 2000-2009 are combined by plotting against day of year (ordinal day) to highlight seasonal pattern.

The seasonal patterns of nitrate concentration from a set of diverse Colorado lakes show that the availability of inorganic nitrogen can be greatly reduced during the summer. These lakes span a large elevation range, suggesting that seasonal deficiency of, if not limitation by, nitrogen is relatively common. At the very least, the seasonal patterns suggest that nitrogen and phosphorus are closely balanced in many Colorado lakes. Accordingly, the Division recommends development of criteria for both nitrogen and phosphorus, while holding open the possibility that a defensible case for site-specific criteria might not require both.

Response of Algae to Nutrients in Colorado Lakes

A quantitative relationship between chlorophyll and phosphorus, or chlorophyll and nitrogen, is necessary for development of phosphorus, or nitrogen, criteria consistent with the target trophic condition. The linkage between causal and response variables is often called a stressor-response relationship, but “stressor” is not a particularly apt term for nutrients. Unlike copper and zinc, phosphorus and nitrogen are not toxic to algae. Nutrient enrichment encourages algal growth, but causes no impairment directly (at least not at the concentrations relevant to criteria development). Instead, it is the consequences of excessive algal growth that are potentially injurious to uses, as described in *“Algal Abundance and Water Quality Impacts.”*

The Division elects to characterize the relationships between algae and nutrients as algal response relationships rather than stressor-response relationships. However, the role in criteria development is the same. Development of criteria from empirical algal response relationships builds on the well-established fact that anthropogenic nutrient enrichment is the cause of cultural eutrophication, a phenomenon with widespread adverse impacts to water quality.

The relationships between chlorophyll and nutrients have been explored for grab samples from Colorado lakes, and they are very similar to those observed for other large sets of lakes. Both sets contain "noise" or scatter in the sense that there is unexplained variability. As noted previously in "*Characterizing Algal Abundance,*" time series graphs show that chlorophyll concentration varies considerably on a relatively short time scale. Aggregating the data by calculating summer average concentration is a common practice that greatly reduces the scatter in the points; aggregated data have been used to develop some of the well-known empirical relationships between chlorophyll and nutrients (e.g., Dillon and Rigler 1974, Jones and Bachmann 1976).

The Division's proposal for lake nutrient criteria is based on defining the target trophic condition, which would be assessed on the basis of summer average concentrations. At least three samples must be available from the summer months (July-September) in the same year in order to calculate a summer average. Accordingly, summer average concentrations were calculated for chlorophyll, phosphorus, and nitrogen in all Colorado lakes with suitable data. For some lakes, summer averages are available in every year included in this analysis; for other lakes, an average can be computed in only one year.

Calculating averages from the summer grab samples reduces the scatter in the relationship between chlorophyll and total phosphorus, which was derived from 282 lake-years representing 54 lakes (Figure 38). As with the grab samples, the upper bound for responsiveness of the algal community is about 1 ug chlorophyll per ug total phosphorus.

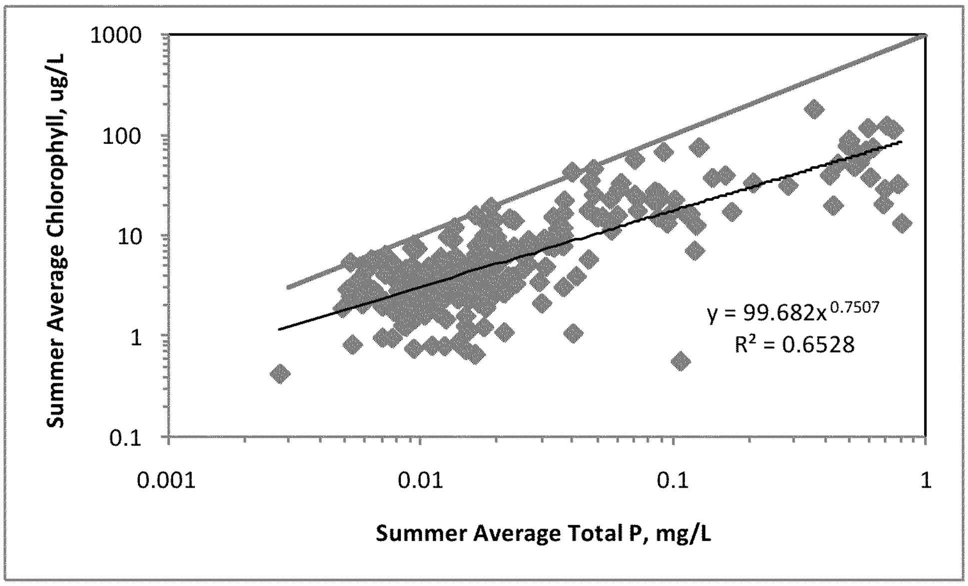

Figure 38. Relationship between summer average concentrations for chlorophyll and total phosphorus. Each point represents the same year for both constituents from the same lake (i.e., one lake -year). The thick, solid line indicates where algal abundance has reached the capacity defined by the corresponding phosphorus concentration. A power function is fitted to the data (thin, solid line), and the equation is inset at the lower right of the figure.

Summer average concentrations for chlorophyll and nitrogen are available for 121 lake-years representing 30 Colorado lakes (Figure 39). The fit of the line is comparable to that presented for phosphorus. Summer averages for chlorophyll are generally well below the potential expected on the basis of the summer average nitrogen, possibly reflecting the tendency for nitrogen deficiency to be seasonal.

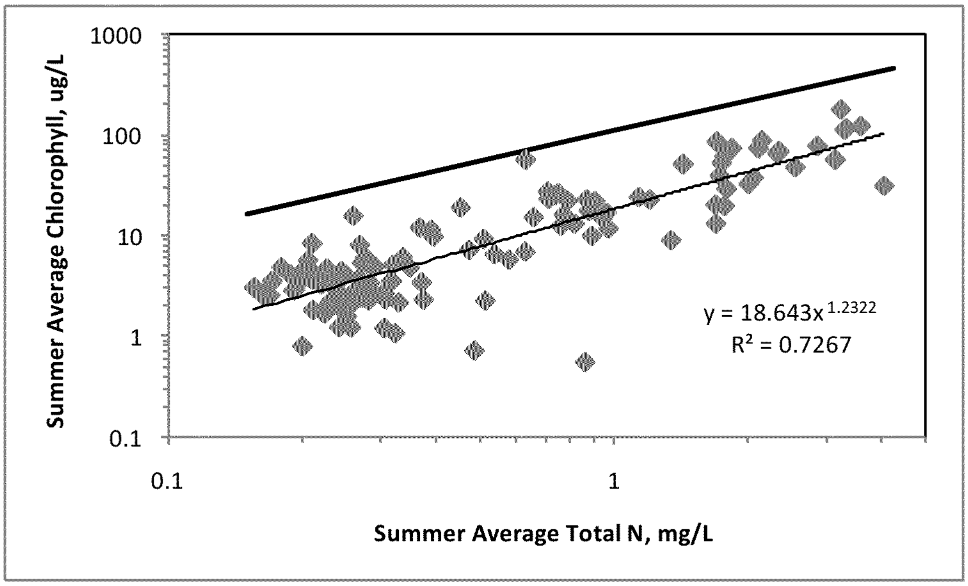

Figure 39. Relationship between summer average chlorophyll and summer average total nitrogen concentrations. Each point represents the same year for both constituents from the same lake (i.e., a lake -year). The thick, solid line indicates where algal abundance has reached the capacity defined by the corresponding nitrogen concentration. A power function is fitted to the data (thin, solid line), and the equation is inset at the lower right of the figure.

Algal Response Summary

Algae will tend to grow to the capacity that a lake can sustain based on the availability of nutrients. Often, however, that capacity is not achieved because abundance is continually being eroded by loss processes that include grazing, settling, and washout. Abundance will increase or decrease in response to the dynamic balance of growth and loss processes.

Shifts in the balance of growth and loss processes inject variability into the relationship between chlorophyll and nutrients. The variability is expected, but problematic to the extent that it leaves more uncertainty regarding the acceptable level of nutrients. The regulatory challenge is to decide how to cope with the variability without compromising protection of uses.

A fully mechanistic explanation of variability in chlorophyll concentration is neither practical nor necessary. The list of processes and variables would be quite long, and it would never be possible to measure everything on a routine basis. Furthermore, it is not clear what regulatory purpose would be served by incorporating all mechanisms that can affect algal abundance.

Variability for chlorophyll measurements can be handled in aggregate by developing simple algal response relationships based on summer average concentrations of chlorophyll and phosphorus, or nitrogen. The relationships are the best way to describe central tendency for the trophic conditions that are the proposed regulatory targets.

Power functions are used to characterize the empirical relationships observed between summer average concentrations of chlorophyll and phosphorus and of chlorophyll and nitrogen. These relationships are used in a later section to define central tendency for each target trophic condition.

Equation 1. Summer average chlorophyll concentration (Chl) in ug/L as a function of summer average total phosphorus (TP) in mg/L.

Equation 2. Summer average chlorophyll concentration (Chl) in ug/L as a function of summer average total nitrogen (TN) in mg/L.

7. Algal Abundance and Water Quality Impacts

Algae affect water quality in lakes, and the significance of those effects increases as the algae become more abundant. Some effects occur while algae are actively growing (elevated pH, toxin production, disinfection byproduct formation potential, taste-and-odor problems), some occur when algae die and decompose (oxygen depletion and related release of metals and nutrients from sediment), and others happen simply because the algae are there (chiefly aesthetic concerns like clarity and bloom formation). In all cases, the effects are more pronounced when algae are abundant.

Excessive abundance of algae also can affect ecological relationships within a lake, leading to alterations in the composition of other aquatic communities and changes in the productivity of sport fisheries (more in "*Policy and the Approach to Nutrient Criteria Development*"). In addition, very high pH (>9.3) may be an indicator of important changes within the algal community. A recent study of Minnesota lakes noted that all but one of the lakes with moderate to high microcystin (a cyanotoxin) concentrations had pH of 9.3 or greater (Lindon & Heiskary 2007).

The level of algal abundance that produces a significant effect may vary among the water quality or ecological characteristics that have been mentioned. Consequently, it is useful to regard the evaluation of each relationship as a line of evidence that can be used in developing criteria for algal abundance (defined operationally by chlorophyll concentration). To the extent possible, the lines of evidence are developed with data from Colorado lakes.

Relationship between pH and Chlorophyll in Lakes

The primary metabolic activities of algae – respiration and photosynthesis – can alter the pH of lake water by adding or removing inorganic carbon (Stumm and Morgan 1970). Respiration produces carbon dioxide (CO_2), which increases the concentration of inorganic carbon and decreases the pH. Photosynthesis consumes inorganic carbon and increases the pH. The potential for photosynthesis to elevate pH in the mixed layer is of regulatory concern because the habitat is important for many aquatic organisms. For support of the aquatic life use, the upper criterion value for pH is 9.0, and this value applies to all surface waters (i.e., all lakes and streams whether classified as Warm or Cold).

The pH of lake water is governed by the carbonate-bicarbonate buffering system[47]. When algae remove inorganic carbon from lake water, it disrupts the equilibrium of the buffering system, causing pH to rise. At the same time, however, gas exchange with the atmosphere, which occurs independently of

[47] See Wetzel 2001 for a thorough description of the buffering system.

biological processes, operates to overcome the CO_2 "deficit" and restore the equilibrium of the buffering system. For pH to increase noticeably, the demand for inorganic carbon (i.e., photosynthesis) must outstrip the rate at which gas exchange can restore it.

The demand for inorganic carbon is determined by the abundance and the growth rate of the algae; demand is greatest when algae are both abundant and growing rapidly.[48] Abundance is measured routinely, as chlorophyll concentration, but growth rates are rarely available. From a regulatory perspective, it would be useful to identify an abundance threshold above which the likelihood of pH greater than 9.0 is too high.

The derivation of an abundance threshold associated with potential pH exceedances is focused on the summer months (July - September) for several reasons. Summer is the season that the Division has proposed for assessing chlorophyll data for attainment of the aquatic life use. Growth rates are highest in the summer because water temperatures are highest[49]. Algal abundance often is high during the summer. Finally, at higher temperatures, the equilibrium concentration of CO_2 is lower, and this means less inorganic carbon is available to meet demand (although re-supply occurs more quickly because gas exchange with the atmosphere also is temperature-dependent).

Simultaneous measurements of chlorophyll and pH have been taken during the summer from 150 lakes in Colorado. These lakes provide broad geographical coverage and good representation of both Warm and Cold lakes. Chlorophyll and pH samples were taken near the surface at the same location; pH values typically represent the 1.0 meter measurement in a vertical profile. Analysis is restricted to samples taken during the summer (July - September) to be consistent with the averaging period proposed for the criteria and because those are the months when elevated pH is most likely to be observed. Analysis also is restricted to data collected since 1990.

The relationship between pH and chlorophyll (algal abundance) is "noisy," but not without pattern. The general tendency is for higher pH to be associated with higher algal biomass in Warm lakes (Figure 40) and in Cold lakes (Figure 41). Most of the pH values above 9.0 are associated with chlorophyll concentrations above 10 ug/L.

[48] Total demand is the product of biomass and growth rate. Increasing either factor increases the demand.
[49] Biological reactions are temperature-dependent and proceed much faster in summer than in winter, other things being equal.

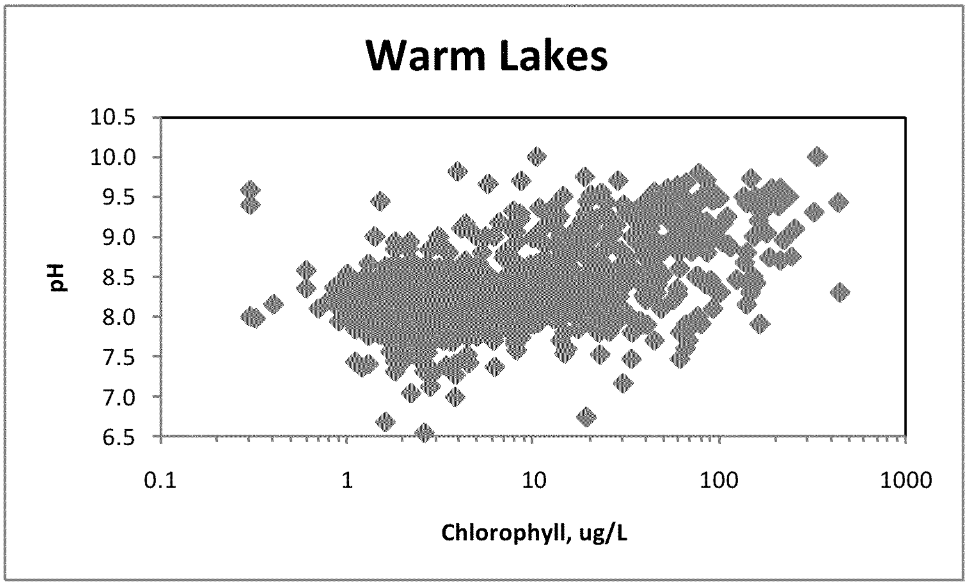

Figure 40. Relationship between pH and algal abundance (chlorophyll) for grab samples in Warm Water lakes.

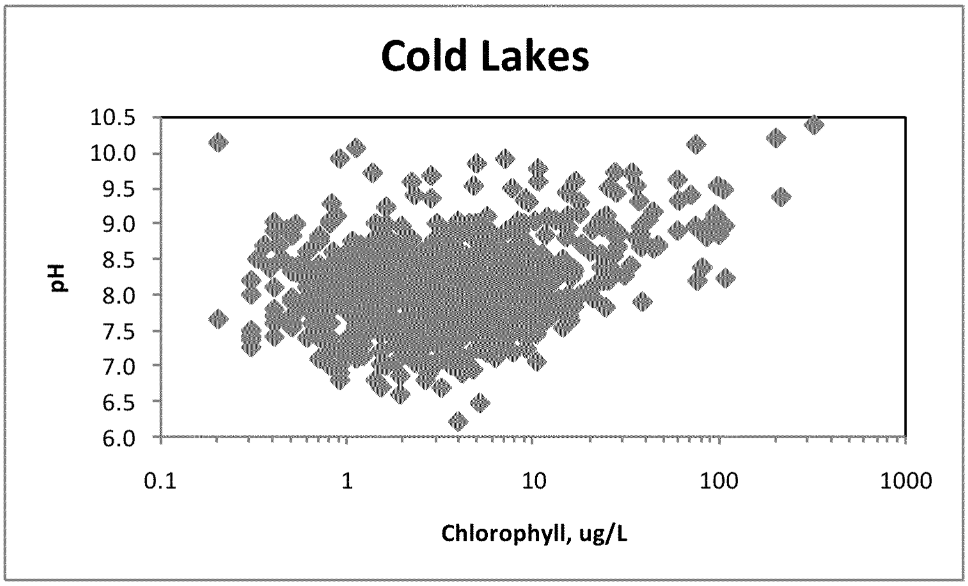

Figure 41. Relationship between pH and algal abundance (chlorophyll) for grab samples in Cold Water lakes. One value with chlorophyll <0.1 ug/L omitted to avoid scale compression.

The importance of high algal biomass is easier to see after the pH values are aggregated within 20 "bins" of ranked (increasing) chlorophyll concentration. Each bin contains approximately 5% of the data points. Box plots are used to summarize the data within each bin and to compare among bins for Warm lakes (Figure 42) and Cold lakes (Figure 43). The data are summarized, and two additional characteristics – the probability that pH will exceed 9.0 and the 85^{th} percentile for pH –are added for each of the 20 bins of Warm lake data (Table 13) and in Cold lake data (Table 14). The 85^{th} percentile value of pH is shown because it represents what would be used for assessment.

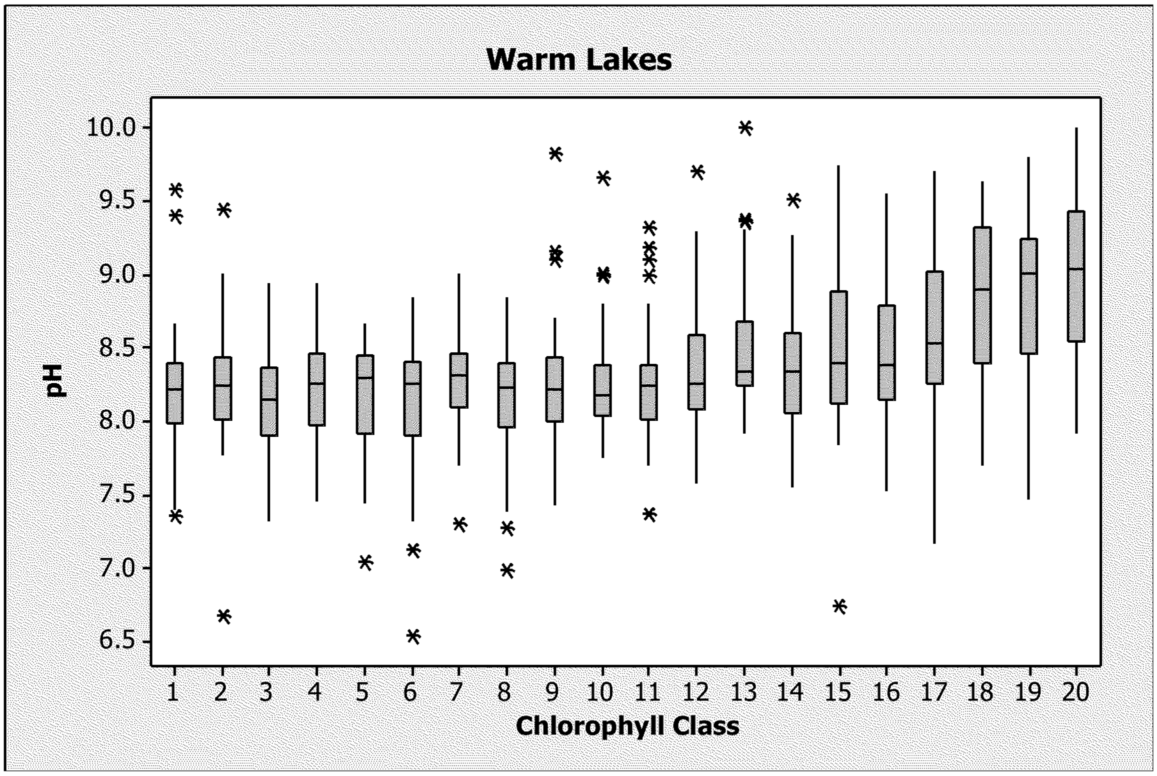

Figure 42. Box plots of pH values within each of 20 bins of ranked (increasing) chlorophyll concentration in Warm Lakes. Each bin contains approximately 5% of the data points.

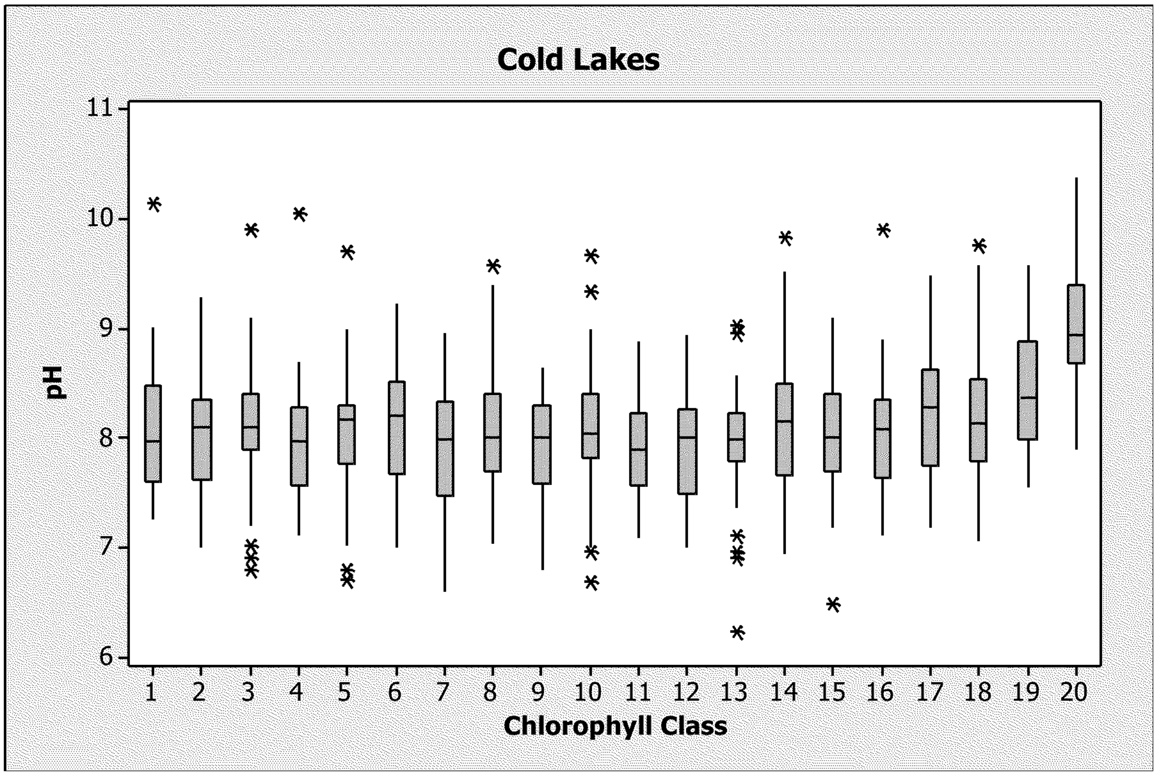

Figure 43. Box plots of pH values within each of 20 bins of ranked (increasing) chlorophyll concentration in Cold Lakes. Each bin contains approximately 5% of the data points.

Class	Number of samples	Chlorophyll	Median pH	Probability (pH>9.0)	85th percentile
1	44	1.1	8.22	3.6%	8.48
2	41	1.5	8.24	2.5%	8.44
3	47	1.8	8.15	0.0%	8.44
4	43	2.1	8.26	0.0%	8.51
5	42	2.4	8.30	0.0%	8.47
6	39	2.6	8.25	0.0%	8.44
7	50	3.0	8.31	0.0%	8.51
8	43	3.5	8.23	0.0%	8.47
9	45	4.3	8.22	5.2%	8.56
10	43	5.5	8.17	4.8%	8.50
11	44	6.9	8.24	7.0%	8.64
12	44	8.7	8.26	11.1%	8.81
13	42	11.5	8.34	18.3%	9.17
14	43	14.7	8.34	9.6%	8.87
15	46	19.5	8.39	20.0%	9.10
16	44	24.9	8.39	19.4%	9.09
17	42	33.8	8.54	24.4%	9.27
18	45	48.8	8.90	38.7%	9.42
19	44	72.7	9.00	53.5%	9.45
20	44	154.8	9.04	53.5%	9.50

Table 13. Characterization of pH values associated with chlorophyll concentration bins for Warm lakes. Sample size and median chlorophyll is given for each bin. The pH values in each bin are characterized on the basis of median value, probability of exceeding pH 9.0, and the 85th percentile value.

Class	Number of Samples	Chlorophyll	Median pH	Probability (pH>9.0)	85th percentile
1	40	0.4	7.98	4.3%	8.71
2	48	0.7	8.10	4.3%	8.59
3	40	1.0	8.10	3.4%	8.45
4	40	1.2	7.97	2.0%	8.41
5	50	1.4	8.17	2.1%	8.43
6	46	1.7	8.20	2.2%	8.61
7	42	2.0	8.00	0.0%	8.40
8	37	2.3	8.00	4.6%	8.42
9	45	2.7	8.00	0.0%	8.41
10	51	2.9	8.04	4.0%	8.47
11	38	3.3	7.90	0.0%	8.50
12	43	3.6	8.00	0.0%	8.34
13	50	4.1	7.99	0.9%	8.40
14	41	4.6	8.15	7.5%	8.80
15	47	5.5	8.00	2.2%	8.57
16	44	6.6	8.08	2.1%	8.47
17	42	8.1	8.29	7.4%	8.75
18	46	10.6	8.13	13.7%	8.89
19	44	17.1	8.38	17.6%	9.09
20	44	43.8	8.94	40.5%	9.53

Table 14. Characterization of pH values associated with chlorophyll concentration bins for Cold lakes. Sample size and median chlorophyll is given for each bin. The pH values in each b in are characterized on the basis of median value, probability of exceeding pH 9.0, and the 85th percentile value.

In general, Warm lakes tend to have higher chlorophyll than Cold lakes, and the baseline pH – typical pH at low chlorophyll concentration – tends to be slightly higher. Higher baseline pH may reflect higher alkalinity, which would be expected for lakes with larger watershed areas (typically at lower elevations in a drainage basin). However, there is considerable similarity between Cold and Warm lakes in terms of the level of algal abundance likely to yield elevated pH.

The probability that summer pH will exceed 9.0 is essentially the same for Warm and Cold lakes when plotted on the same scale for chlorophyll (Figure 44). The probability rises sharply as the typical chlorophyll concentration exceeds about 5 or 6 ug/L. A similar plot shows the 85th percentile value for pH as a function of chlorophyll concentration (Figure 45). There appears to be little difference between Cold and Warm lakes, with both showing a pH response when chlorophyll concentrations exceed 4 or 5 ug/L.

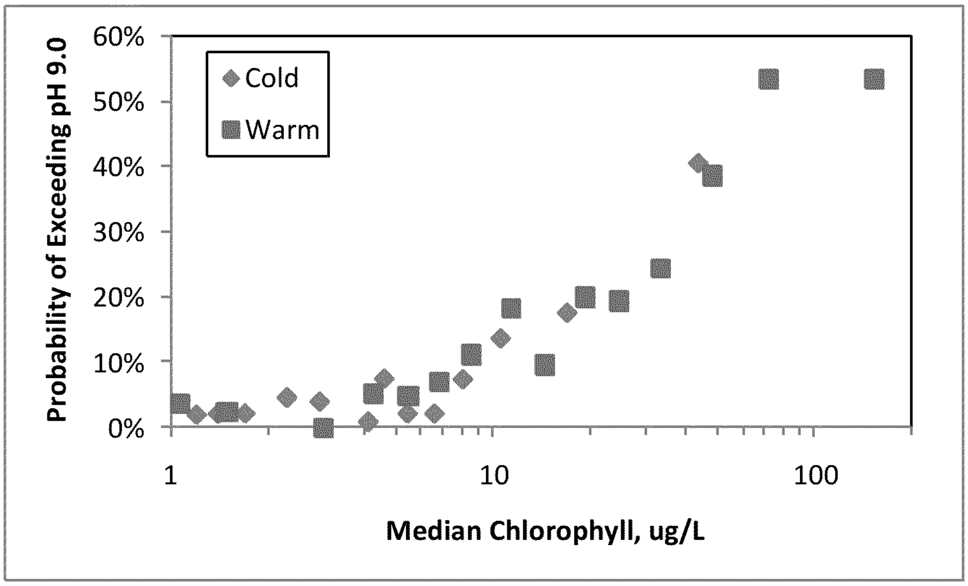

Figure 44. Probability that summer pH will exceed 9.0 as a function of chlorophyll concentration for Warm and Cold lakes. Chlorophyll concentrations represent the median of those samples in each of the 20 bins for Warm and Cold lakes.

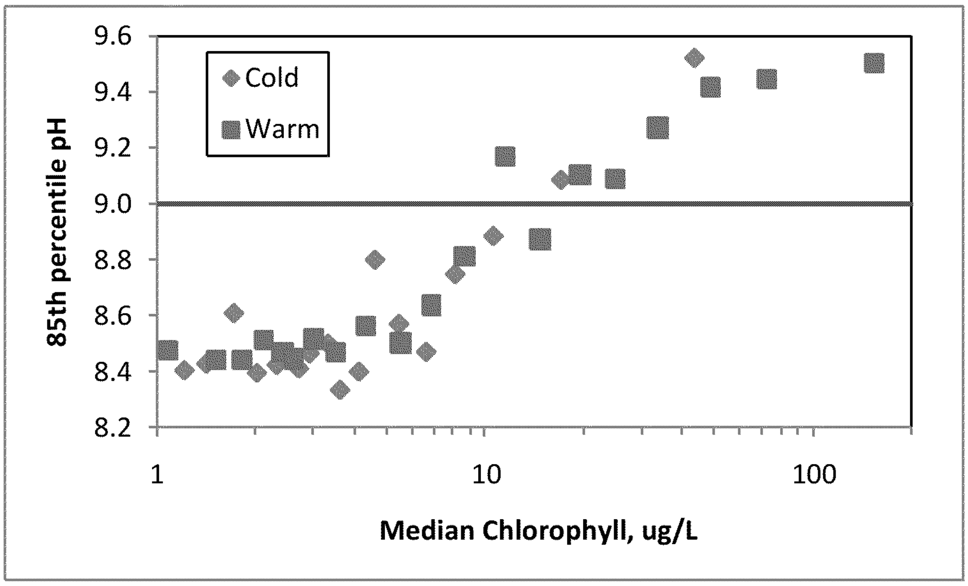

Figure 45. Relationship between pH value derived from assessment methodology and chlorophyll concentration. pH data were divided into 20 bins on the basis of chlorophyll concentration in Cold and Warm lakes. The point plotted for each bin represents the 85th percentile of the pH values and the median of the chlorophyll values.

The relationship between pH and chlorophyll appears to be substantially the same in Cold and Warm lakes. Regression analysis with a dummy variable (as described in "Nutrients and *Algal Abundance*") was used to compare slopes and intercepts of the pH response lines in Cold and Warm lakes. Analysis was restricted to the range of chlorophyll concentrations over which there was a response and where both classes of lakes were represented. The analysis showed that the lines were coincident for both the exceedance probability and the 85th percentile values. Therefore, pH data from Cold and Warm lakes can be combined.

The combined data set, which consists of 1,753 pH-chlorophyll pairs from summer samples, is used to identify a chlorophyll threshold above which the Colorado assessment methodology would indicate a pH exceedance. That methodology compares the pH standard (9.0) to the 85th percentile of observations. The comparison is made separately for each of 20 bins defined on the basis of chlorophyll concentration (Figure 46). A simple trend line locates the typical chlorophyll concentration at which the 85th percentile of pH values will exceed 9.0. The trend line was developed with those points showing departure from baseline pH. The equation for the line can be solved to obtain 16.5 ug/L as the typical chlorophyll concentration above which the 85th percentile value of pH would exceed 9.0. A more detailed version of this assessment is presented in *Defining Trophic Condition*.

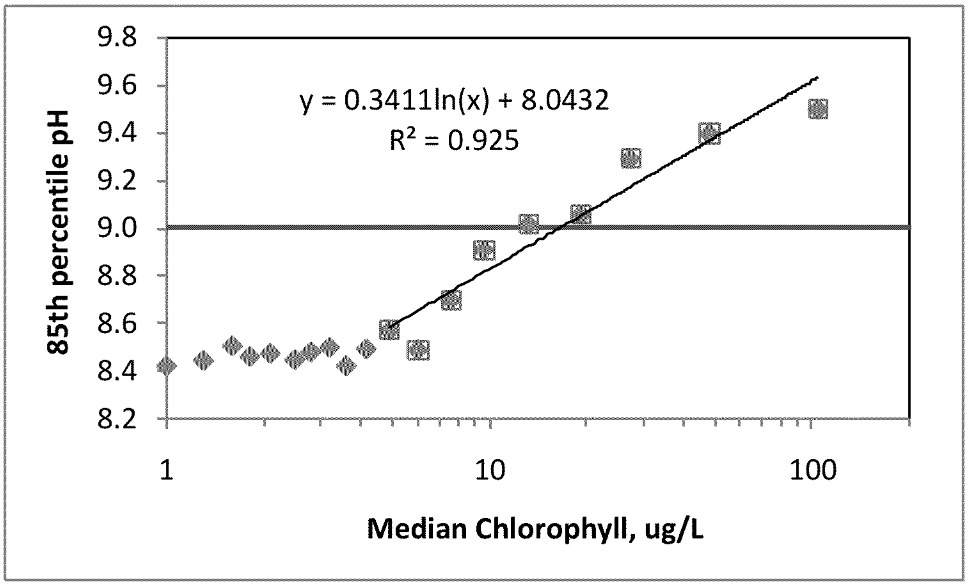

Figure 46. Relationship between pH value derived from assessment methodology and chlorophyll concentration. pH data were divided into 20 bins on the basis of chlorophyll concentration. The point plotted for each bin represents the 85 th percentile of the pH values and the median of the chlorophyll values. Data have been combined from all lakes.

A similar analysis was performed to determine how the exceedance probability changes with increasing pH. The probability of a pH exceedance is essentially zero when chlorophyll is less than about 5 ug/L, and it increases to about 30 percent at the edge of bloom conditions (30 ug/L).

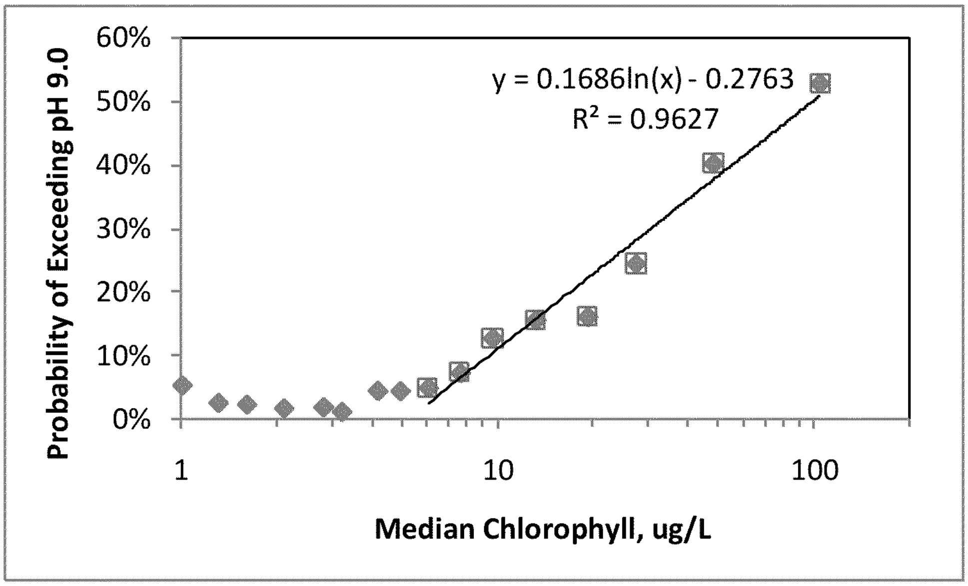

Figure 47. Probability that summer pH will exceed 9.0 as a function of chlorophyll concentration for all lakes. Chlorophyll concentrations represent the median of those samples in each of 20 bins. The regression line does not apply to chlorophyll concentrations less than about 6 ug/L.

Relationship Between Transparency and Chlorophyll

The clarity, or transparency, of a lake often determines its desirability for some forms of recreation, like swimming. Given a choice, most swimmers would probably prefer to see their toes on the bottom than to have the view obscured by algae. Of course, setting a threshold in this manner is difficult because there may be local or regional differences in expectations about transparency (Smeltzer and Heiskary 1990). The purpose of this analysis is to facilitate policy-setting by providing estimates of the transparency expected for any proposed chlorophyll criterion.

Transparency is decreased by the addition of dissolved substances (chiefly dissolved organic carbon) or particulates (algae and non-algal particulate matter). The effect is not the same at all wavelengths of light, but a single number can be derived to characterize transparency in the visible or photosynthetically active range.

Transparency is often measured with a simple device called a Secchi disk; it is lowered into a lake, and the depth at which it just disappears from view is recorded. Although it is simple and yields a single number that represents transparency, it is not easily correlated with the formal optical properties of water (see review in Preisendorfer 1986). The Secchi depth corresponds roughly to the depth at which light has been reduced to approximately 10 percent of intensity at the surface (range 1-15 percent; Wetzel 2001).

Light intensity decreases as a function of depth[50], and several factors contribute to the attenuation of light. Considerable study has been devoted to the task of parsing the attenuation coefficient into the

[50] The ratio of light at depth (I_z) to light at the surface (I_0) declines exponentially with depth (z): where n is the extinction coefficient, which has units of m^{-1}.

major components. The coefficients are usually presented as ranges because the attenuation by dissolved organic carbon (DOC) or by algae depends on composition[51] as well as concentration. As a result, there is often substantial unexplained variability in a relationship between Secchi depth and chlorophyll, for example.

The change in Secchi depth associated with incremental changes in chlorophyll concentration is determined by regression analysis using chlorophyll concentrations that are high enough to make a meaningful contribution (approximately 10%) to the total attenuation of light.

In rough terms, total attenuation (K_d) can be estimated from the Secchi depth (SD) as follows[52]: $K_d = 1.7/SD$. If the Secchi depth is 3 meters, for example, the attenuation coefficient would be about 0.6 meters^{-1}. In a montane lake in mid-summer, attenuation would be due mainly to chlorophyll and DOC. High concentrations of DOC diminish the clarity of lake water by making it look like weak tea.

Using a value of 0.015 meters^{-1} for the chlorophyll-specific attenuation coefficient[53], the chlorophyll concentration would have to be at least 4 ug/L if chlorophyll was to contribute at least 10 percent to the observed attenuation. This is a plausible scenario because the median chlorophyll concentration for Cold lakes with a 3 meters Secchi depth is 4.3 ug/L. DOC could easily account for the remainder of the attenuation[54].

About 2,000 summer measurements of chlorophyll and Secchi depth have been taken from 158 lakes in Colorado. These lakes provide broad geographical coverage and good representation of both Warm and Cold lakes. Chlorophyll was taken near the surface at the same location where the Secchi depth was measured. A few Secchi depths taken with a “view-scope” were omitted[55]. In addition, data are excluded if the chlorophyll concentration was less than 4 ug/L for reasons explained above.

Paired measurements of Secchi depth and chlorophyll are shown on separate graphs for Cold (Figure 48) and Warm (Figure 49) lakes. In each graph, the data show the non-linear relationship expected due to the nature of light attenuation (cf. Megard et al. 1980). Transparency values as high as 10 meters have been recorded in Cold lakes, but only as high as 7 meters in Warm lakes.

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[51] The attenuation from chlorophyll also depends on the size of the particles (algal cells). Packaging the chlorophyll in large bundles – a small number of large cells – has less effect on attenuation than packaging the same amount of chlorophyll in many small cells (Edmondson 1980).

[52] The value of 1.7 in the numerator is widely cited (e.g., Wetzel 2001), but it is empirical and may vary among lakes depending on factors like DOC and turbidity (see Koenings and Edmondson 1991)

[53] The chlorophyll-specific attenuation coefficient is in the range of 0.01 to 0.02 m^{-1} per ug/L of chlorophyll (Megard et al. 1980, Reynolds 2006).

[54] Typical DOC concentrations for montane lakes are in the range of 2-4 mg/L (Morris et al 1995, Division's High Quality Water Supply study). Given a DOC-specific attenuation coefficient of about 0.2 m^{-1} per mg/L of DOC (Morris et al. 1995, Buckaveckas and Robbins-Forbes 2000), a concentration of about 3 mg/L would be sufficient to account for the observed attenuation.

[55] View scopes are used to eliminate surface roughness and glare when measuring Secchi depths. Measurements made with this device will exceed those recorded by the traditional technique(i.e., without benefit of the view scope). To reduce the risk of bias, we have omitted measurements made with the view scope (61 values from five lakes).

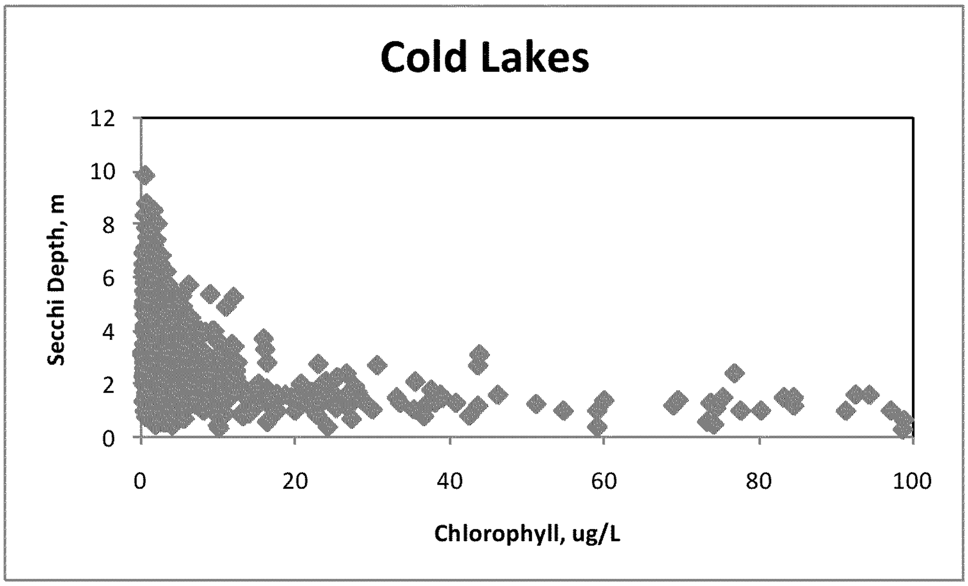

Figure 48. Transparency (Secchi depths) as a function of algal abundance (chlorophyll concentration) during summer months (Jul-Sep) in lakes classified for Cold Aquatic Life. The chlorophyll axis has been truncated at 100 ug/L to avoid scale compression; six points are excluded.

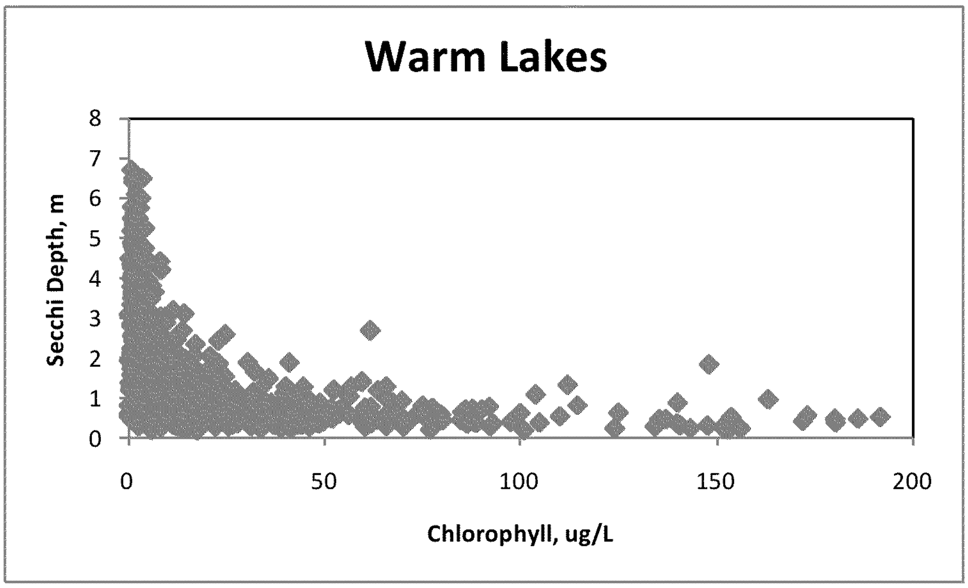

Figure 49. Transparency (Secchi depths) as a function of algal abundance (chlorophyll concentration) during summer months (Jul-Sep) in lakes classified for Warm Aquatic Life. The chlorophyll axis has been truncated at 200 ug/L to avoid scale compression; 12 points are excluded.

The relationship between chlorophyll and light attenuation (proportional to the inverse of Secchi depth) is shown in Figure 50. Both variables are shown on a log scale to spread the values more evenly in the interest of developing a useful empirical relationship (i.e., the aim is not to derive attenuation coefficients based on a theoretical model). Trend lines are almost parallel for Cold and Warm lakes, but the intercepts appear to be quite different. A formal comparison of the lines using regression with a dummy variable (as explained in "*Characterizing Algal Abundance*") confirms that they are parallel, and the intercepts are significantly different. The difference between intercepts may reflect a larger contribution from non-algal particulates (inorganic turbidity) in Warm lakes, many of which are shallow and on the plains.

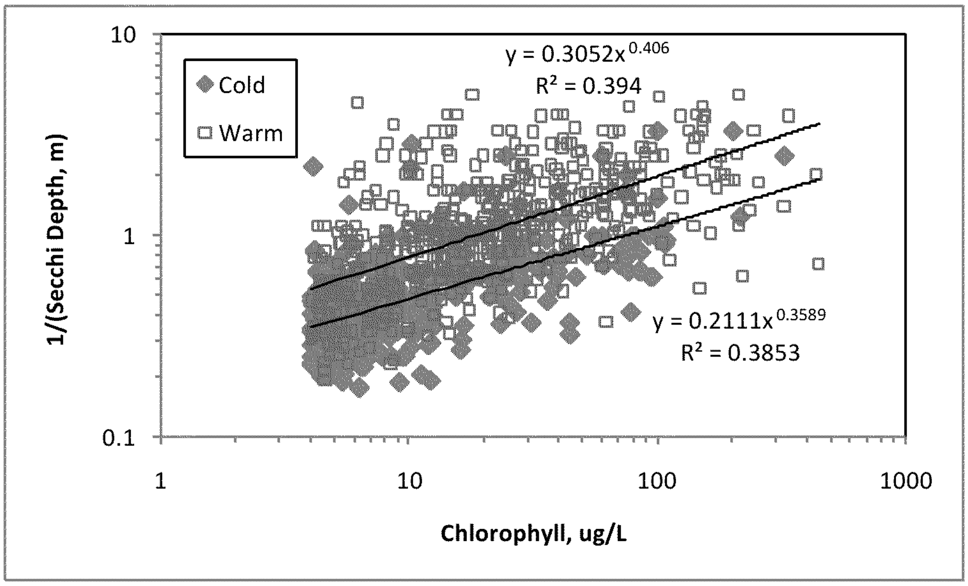

Figure 50. Relationship between light attenuation (inverse of Secchi depth) and chlorophyll concentration for summer measurements in Cold and Warm lakes. Larger numbers on the vertical axis mean less transparent water.

The revised dummy regression analysis (Figure 51), which omits the interaction term associated with slope, results in separate equations for Cold lakes and Warm lakes:

Equation 3. The inverse of Secchi depth as a function of chlorophyll concentration for Cold lakes.

Equation 4. The inverse of Secchi depth as a function of chlor ophyll concentration for Warm lakes.

Regression Analysis: LN(1/Secchi) versus LN(chl), Dummy

```
The regression equation is
LN(1/Secchi) = - 1.62 + 0.389 LN(chl) + 0.486 Dummy


Predictor      Coef  SE Coef       T      P
Constant   -1.62357  0.04093  -39.67  0.000
LN(chl)     0.38943  0.01538   25.33  0.000
Dummy       0.48603  0.03181   15.28  0.000


S = 0.468720   R-Sq = 56.7%   R-Sq(adj) = 56.6%


Analysis of Variance

Source            DF      SS      MS       F      P
Regression         2  288.31  144.16  656.16  0.000
Residual Error  1003  220.36    0.22
Total           1005  508.67
```

Figure 51. Dummy regression analysis of the inverse of Secchi depth vs. chlorophyll. Both variables are log-transformed. The lines for Cold and Warm lakes are parallel, but have different slopes.

Bloom Formation Frequency

In any lake, algal abundance varies over time, and the changes in abundance can occur quite rapidly. During the summer months, algae can double their numbers within a few days. Of course, algal abundance does not expand indefinitely because there are limits – set mainly by the nutrient supply – to the carrying capacity of a lake.

The observed variability in algal abundance represents the dynamic balance of growth and loss processes. The relative importance of those factors changes constantly, causing algal abundance to rise or fall rapidly throughout the summer. However, it is usually the rapid increases that attract attention because it is the high levels of abundance that become visually conspicuous.

High levels of algal abundance are generally regarded as undesirable from an aesthetic perspective because of the visual impact of surface scums of algae and because of the unpleasant odors produced when those algae decay. The sudden appearance of algae in abundance is often referred to as a "bloom"[56] and considerable effort has been expended on defining the chlorophyll level that constitutes a bloom.

One scheme that has persisted in the literature was presented by Walmsley (1984), who defined three thresholds. When chlorophyll concentrations exceeded 10 ug/L, surface scums were evident.

[56] According to Reynolds (2006), "water bloom" was applied originally only to those instances where Cyanobacteria, which have gas vacuoles that can make them buoyant, formed a conspicuous scum on the surface. Now, the term is used broadly to characterize algal abundance without regard to taxonomic composition.

Concentrations above 20 ug/L were considered indicative of "nuisance" conditions and those in excess of 30 ug/L constituted "severe nuisance" conditions.

Severe nuisance blooms do not appear in every lake. Many do not have nutrient concentrations adequate to enable algae to grow to that level of abundance. Even for those lakes with sufficient nutrients, the appearance of bloom conditions is unpredictable, making assessment more difficult. Fortunately, the likelihood of bloom conditions is strongly related to the average chlorophyll concentration (Walker 1985).

The Division has taken an empirical approach in developing a relationship between bloom frequency and typical summer average chlorophyll concentration (see "*Characterizing Algal Abundance*"). The frequency of severe nuisance bloom conditions is negligible when the typical summer average concentration is less than about 15 ug/L, but it rises sharply at higher average concentrations (Figure 52).

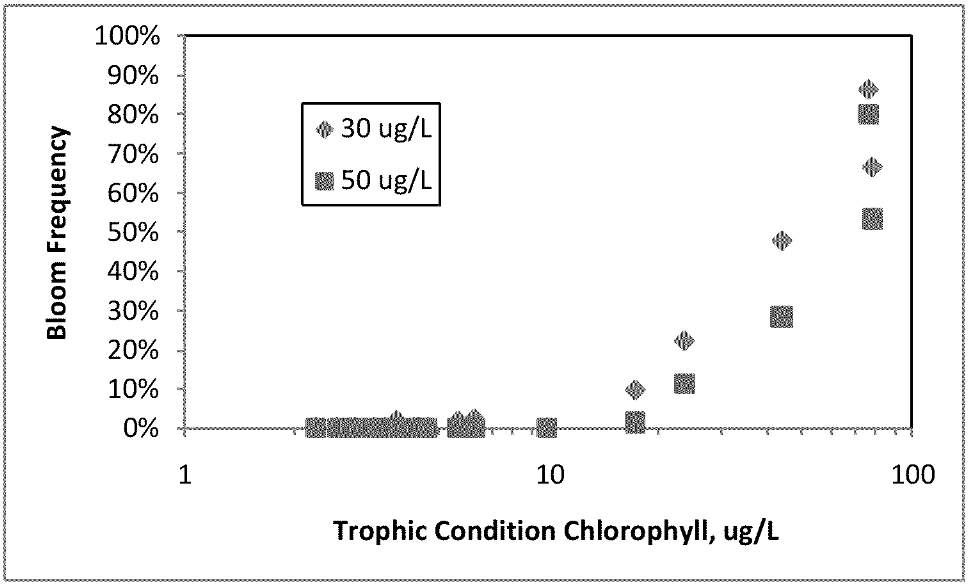

Figure 52. Frequency of summer algal blooms observed in Colorado lakes of different trophic condition (as indicated by typical summer average chlorophyll concentration). Bloom thresholds of 30 and 50 ug/L are included.

More detail about the relationship between the risk of blooms and the target trophic condition is presented in "*Defining Trophic Condition.*"

Water Quality Concerns Related to Abundance of Cyanobacteria

Cyanobacteria have been called the "predominant harbingers of cultural eutrophication" because of their tendency to proliferate where nutrient enrichment has occurred (Burkholder 2009). They have morphological and physiological characteristics, such as buoyancy regulation, that make them well-adapted to form blooms. It is generally the case that as algal abundance increases Cyanobacteria become an increasingly important component of the community. When chlorophyll concentrations exceed about 10 ug/L, the risk of dominance[57] by Cyanobacteria increases sharply (Downing et al. 2001).

Blooms of Cyanobacteria raise concerns related to human health, livestock, drinking water treatment, and lake ecology. Many species of Cyanobacteria are known to produce one or more of the various toxins that have been identified (Burkholder 2009). Lethal effects of toxins have been reported widely for livestock, and toxins are known to have sickened humans (famously including Senator Inhofe of Oklahoma[58]). The Cyanobacteria also are considered the "chief sources" of common taste and odor compounds (geosmin and 2-methyl-isoborneol)(Juttner and Watson 2007). In addition, Cyanobacteria are less suitable as food for herbivores than are other taxa like the green algae (Chlorophyta). Consequently, an abundance of Cyanobacteria may not bode well for the transfer of energy to higher trophic levels (i.e., from algae to herbivores to fish).

Selecting a threshold of concern for the abundance of Cyanobacteria is difficult because there are no absolute guidelines. One useful approach has been developed by the World Health Organization for recreational use of water (WHO 2003). Guidelines are established based on estimates of risk using assumptions regarding the species composition of the algal community, the amount of toxin produced by each cell, and the volume of water that might be ingested. For example, the threshold for "moderate probability of adverse health effects" can be expressed as 50 ug chlorophyll per liter or 100,000 cells/mL. The threshold is useful because it provides a basis for screening the available algae data from Colorado in a search for general patterns.

Available Phytoplankton Data

The WQCD has been taking phytoplankton samples as a routine component of lake monitoring since 2001. Almost 300 samples, mostly from summer months, have been analyzed from 80 lakes. The algae in these samples have been identified to species level, and the abundance of each species has been determined quantitatively by enumeration of subsamples.[59] In addition, data from other sources are available for several lakes that have been studied intensively over many years (Table 15). These third party data are particularly useful for examining seasonal patterns of abundance because samples were taken in most months of the year.

Lake	Period of Record	Number of samples	Source	Comment
Barker	2000-2010	123	City of Boulder	Ice-free season
Bear Creek	1996-2008	269	Bear Creek Watershed Association	
Boulder	2000-2010	70	City of Boulder	Ice-free season
Chatfield	1992-2007	78	Chatfield Watershed Authority	
Cherry Creek	1996-2008	214	Cherry Cr Basin Water Quality Authority	
Dillon	2005-2009	42	Summit Water Quality Committee	

57 Dominance was defined as having Cyanobacteria comprise at least half of community biomass.
58 Reported in Tulsa World 7/6/2011.
59 Phytoplankton samples are taken directly from the near-surface integrated water sample that is used for all chemical analyses. The phytoplankton sample is not filtered. A subsample is settled in a chamber that is examined with an inverted microscope.

Lake	Period of Record	Number of samples	Source	Comment
Green Mountain	2007, 2009	24	Summit Water Quality Committee	

Table 15. Lakes for which phytoplankton data was provided by third party sources.

Seasonal Patterns of Abundance

The existence of strong seasonal patterns in the abundance of Cyanobacteria could influence decisions analysis of available data, as well as the design of future monitoring programs. The best opportunities for examining seasonal patterns are with several well-studied lakes. Those with particularly good seasonal coverage for many years include Bear Creek, Cherry Creek, and Chatfield reservoirs, all of which are subject to control regulations.

Phytoplankton samples have been taken from Bear Creek Reservoir since late 1990. A wide range of chlorophyll and nutrient concentrations have been recorded in the reservoir. Nutrient loads were reduced sharply by 1995 after improved treatment was implemented by wastewater dischargers. Despite reduced load, chlorophyll concentrations indicate that the reservoir remains in the eutrophic range due largely to the influence of internal phosphorus load. Cyanobacteria tend to be most abundant during late summer (Figure 53); 75 percent of the dates with more than 100,000 cells/mL were in August and September. This is the time of year when chlorophyll concentrations also tend to be highest in this reservoir.

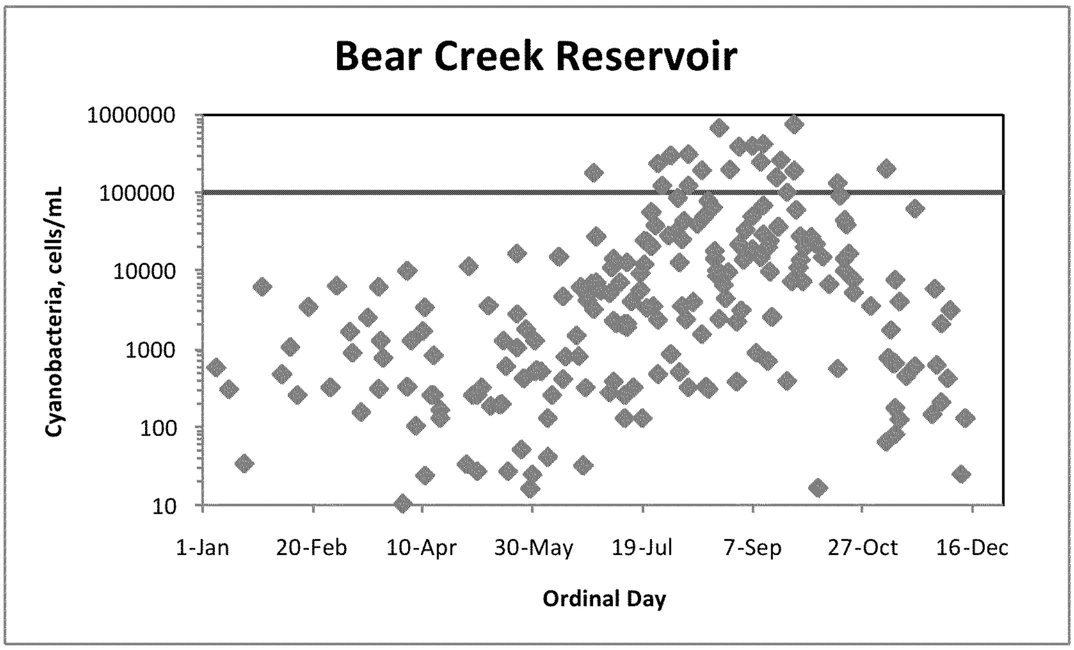

Figure 53. Abundance of Cyanobacteria in Bear Creek Reservoir, 1990-2008. All values have been plotted against ordinal day to highlight seasonal patterns. A few dates with fewer than 10 cells/mL have been omitted to reduce scale compression. The solid line indicates the WHO guideline value for recreational risk.

Phytoplankton samples have been taken in Cherry Creek Reservoir since 1996. In general, algae are more abundant in Cherry Creek Reservoir than in Bear Creek Reservoir, and both reservoirs show a typical pattern of high chlorophyll in late summer. The same is true of the Cyanobacteria, which may exceed 100,000 cells/mL in any month (Figure 54). However, exceedances of this abundance threshold are much more likely in August and September than in any other month. In those two months, about half of the sampling dates exceeded the threshold, whereas in the winter months (November - March) only 20 percent exceeded the threshold.

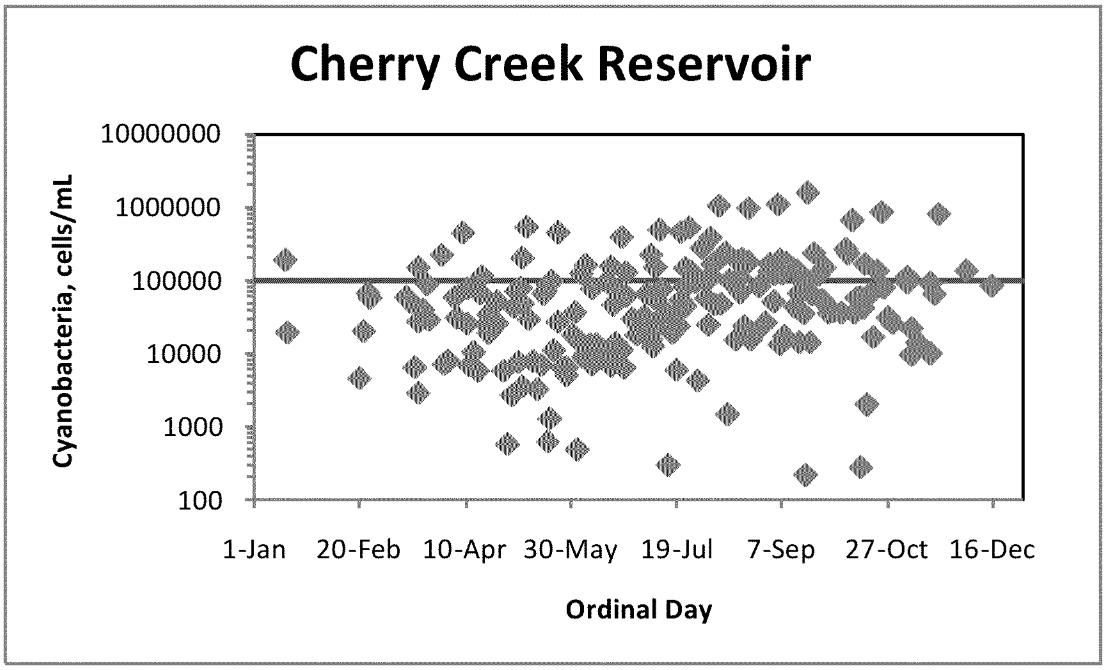

Figure 54. Abundance of Cyanobacteria in Cherry Creek Reservoir, 1996-2008. All values have been plotted against ordinal day to highlight seasonal patterns. Twelve dates with fewer than 100 cells/mL have been omitted to reduce scale compression. The solid line indicates the WHO guideline value for recreational risk.

In Boulder Reservoir, where fewer samples are available, high levels of Cyanobacteria tend to be confined to the summer months, albeit for a broader time window – July - October – than observed for Bear Creek and Cherry Creek reservoirs (Figure 55). September and October tend to be the months with highest chlorophyll.

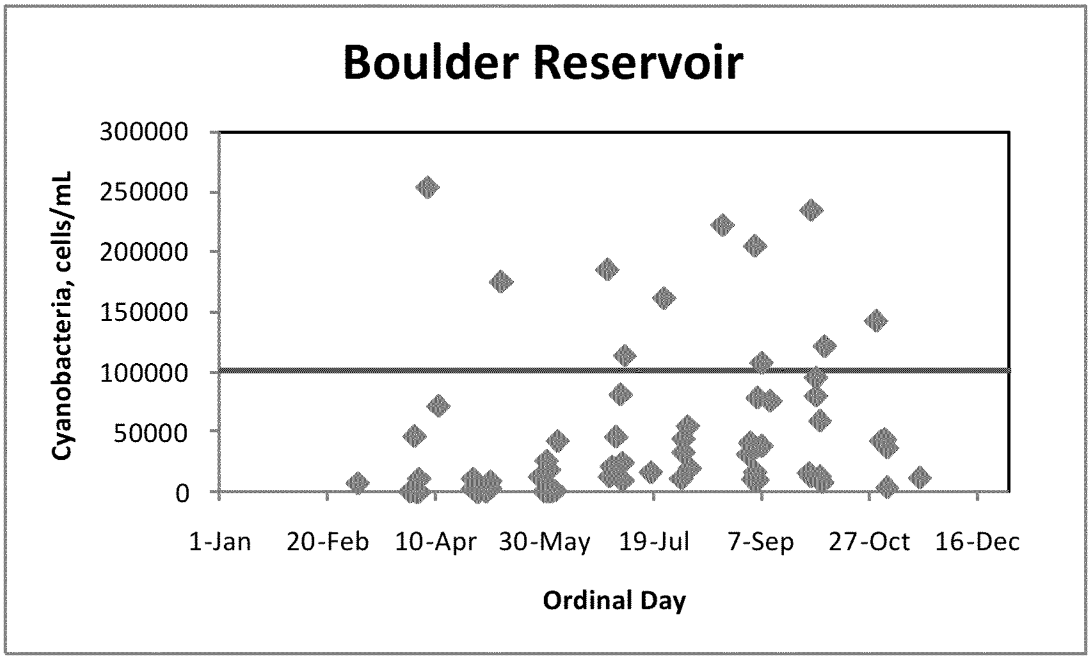

Figure 55. Abundance of Cyanobacteria in Boulder Reservoir, 2000-2010. All values have been plotted against ordinal day to highlight seasonal patterns. The solid line indicates the WHO guideline value for recreational risk.

The other reservoirs with strong data records do not sustain high levels of algal abundance. In Chatfield Reservoir, for example, there are only four dates, out of 78 sampled, when the abundance of Cyanobacteria exceeded 100,000 cells/mL. These dates were in late July and August. In Barker, Dillon, and Green Mountain reservoirs, observed abundance never approached the threshold.

Chlorophyll and Cyanobacteria Abundance

The abundance of Cyanobacteria in Colorado lakes tends to be higher in the summer, and higher in Warm lakes than in Cold lakes (Figure 56). Cell counts rarely exceed the WHO guideline value in Cold lakes at any chlorophyll level. However, it is relatively common to exceed the guideline value in Warm lakes, most of which are eutrophic or more productive, especially when the chlorophyll concentration is in excess of about 10 ug/L. Comparable plots from Bear Creek Reservoir[60] (Figure 57) and Cherry Creek Reservoir (Figure 58) suggest a similar pattern.

[60] Bear Creek Reservoir is classified for Cold Water Aquatic Life, but it is located at the downstream edge of Cold segments in the Bear Creek drainage, and it has a site-specific temperature standard. In addition, nutrient concentrations are higher than is typical of most Cold lakes.

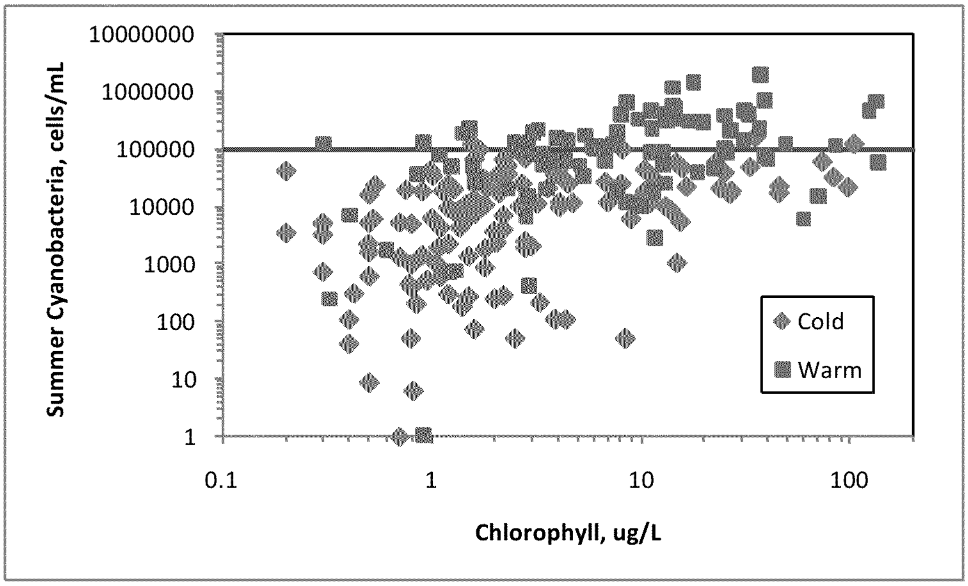

Figure 56. Density of Cyanobacteria (cells/mL) as a function of chlorophyll concentration (ug/L) in summer grab samples collected by WQCD. Phytoplankton and chlorophyll samples were taken concurr ently. The solid line indicates the WHO guideline value for recreational risk.

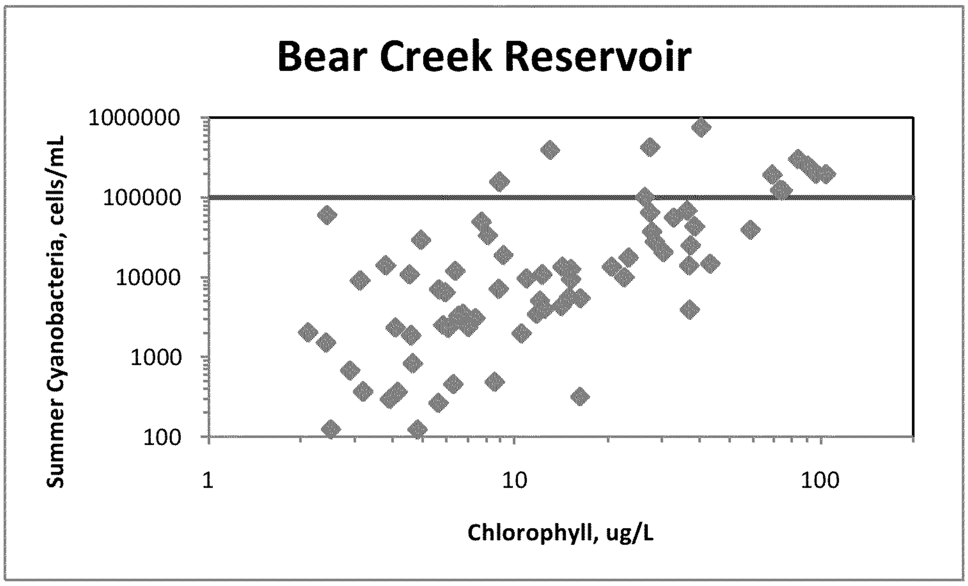

Figure 57. Density of Cyanobacteria (cells/mL) as a function of chlorophyll concentration (ug/L) in summer grab samples from Bear Creek Reservoir. Phytoplankton and chlorophyll samples were taken concurrently. The solid line indicates the WHO guideline value for recreational risk (see text).

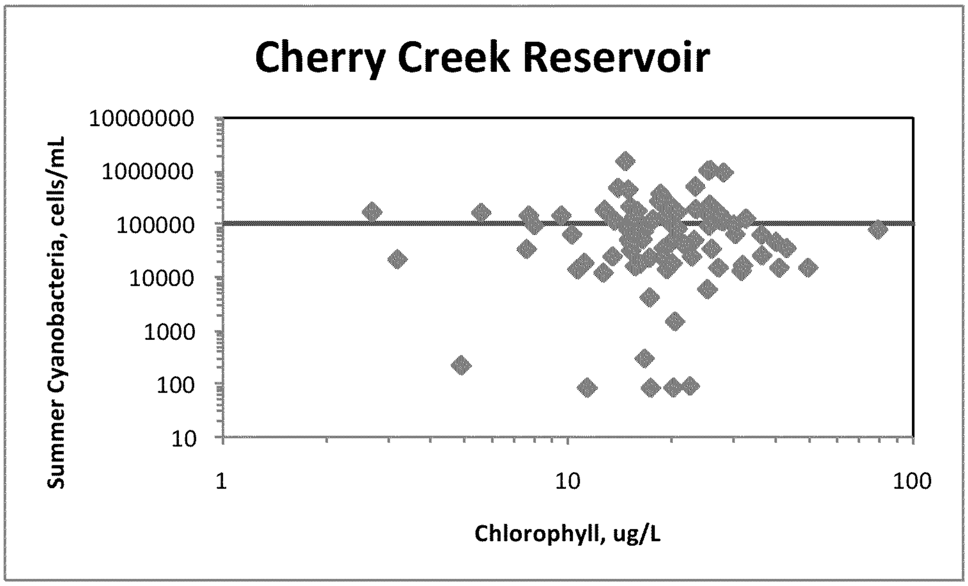

Figure 58. Density of Cyanobacteria (cells/mL) as a function of chlorophyll concentration (ug/L) in summer samples from Cherry Creek Reservoir. Phytoplankton and chlorophyll samples were taken concurrently. The solid line indicates the WHO guideline value for recreational risk (see text).

The relatively low chlorophyll threshold above which Cyanobacteria are likely to exceed the WHO guideline raises a question about assumptions underlying the guideline value. Assumptions about species composition and toxin content are probably very conservative, and this is may be appropriate for a guideline. However, very conservative assumptions about the relationship between chlorophyll and cyanotoxins may not be suitable for establishing chlorophyll criteria in Colorado.

A recent study of Florida lakes shows that one common cyanotoxin – microcystin – is largely undetectable ($\leq$1 ug/L) when chlorophyll is less than 11 ug/L. Microcystin is much more likely to be present at higher chlorophyll concentrations, but do not reach the recreational guidance level of 20 ug/L until chlorophyll exceeds 100 ug/L (Bigham et al. 2009). Chlorophyll concentrations in *most* Colorado lakes do not approach 100 ug/L at any time.

Biomass Equivalents for Potentially Toxic Cyanobacteria

Many species of Cyanobacteria are known to produce one or more of the various toxins that have been identified (Burkholder 2009). The toxins vary in terms of the potential threat to human health, and the potential threat is difficult to quantify unless the amount of toxin is measured directly. However, because direct measurement of toxin concentrations are not available for most Colorado lakes[61], it would be convenient to have a "translator" that would express risk in terms of chlorophyll, for example, which can be measured more easily and is commonly measured in routine monitoring programs.

Translating chlorophyll concentration into a risk factor involves assumptions as is clear from the lengthy explanation accompanying the WHO guidelines. To further illustrate the difficulty, "warning levels" are given for various species known to produce toxins (Table 16). The thresholds, expressed as cell counts

[61] There are a few measurements from lakes sampled as part of the National Lake Assessment conductedby EPA, and some routine measurements – all very low – from Grand Lake.

or filament lengths, show considerable variation among species. Not all of these species have been reported for Colorado. In addition, there a few other species in Colorado that are thought to produce toxins, but for which the warning levels are not available.

Species	Threshold abundance	Units
Microcystis aeruginosa	10,000 – 20,000	cells/mL
Woronichinia naegeliana	40,000 – 60,000	cells/mL
Aphanizomenon flos-aquae	150,000 – 180,000	cells/mL
Anabaena circinalis, A. flos-aquae, A. spiroides	15,000 – 30,000	cells/mL
Anabaena lemmermannii	30,000 – 60,000	cells/mL
Anabaena solitaria	20,000 – 40,000	cells/mL
Planktothrix mougeotii	400 – 550	mm/mL
Planktothrix agardhii	800 – 1,100	mm/mL
Limnothrix redekei	6,000 – 8,000	mm/mL
Pseudanabaena limnetica	16,000 – 20,000	mm/mL

Table 16. Approximate abundance thresholds corresponding to "warning levels" for selected algae known to produce toxins. From Reynolds (2006; Table 8.2).

Of the 13 species with warning level information, 10 have been found in Colorado lakes[62] (Table 17). Only a few of the species have exceeded warning levels often, and most of those cases have occurred in a few, mainly hyper-eutrophic lakes. The species cited most often is *M. aeruginosa*, which is very common and widespread. Most of the "exceedances" have been limited to Bear Creek and North Sterling reservoirs, both of which have characteristically high chlorophyll levels.

Species	N of lakes	Lakes exceeding warning level (events)
Microcystis aeruginosa	7	Jackson (3), Jumbo (2), North Sterling (1), Bear Creek (20%)
Woronichinia naegeliana	5	Bear Creek (18%)
Aphanizomenon flos-aquae	32	North Sterling (1), Bear Creek (4%)
Anabaena circinalis	10	Cherry Creek (<1%)
Anabaena flos-aquae	19	0
Anabaena spiroides	12	North Sterling (1), Cherry Creek (2%)
Anabaena spiroides var crassa	7	Summit (1)
Anabaena lemmermannii	8	Bear Creek (4%)
Anabaena solitaria	0	
Planktothrix mougeotii	0	
Planktothrix agardhii	10	Prewitt (1)
Limnothrix redekei	0	
Pseudanabaena limnetica	34	0

Table 17. Occurrence of selected algal species at densities exceeding "warning levels" as defined by Reynolds (2006). Thresholds for warning levels are shown in Table 2. Not all species have been found in Colorado lakes, and n ot all species have reached densities high enough to meet warning level thresholds. Warning levels for *P. agardhii* and *P. limnetica* were converted to cells/mL using cell lengths of 4 um, which is a typical value for Colorado lakes.

[62] No phytoplankton data were available for four lakes with the highest chlorophyll concentrations– Barr, Milton, Horse Creek, and Prospect.

Warning levels are exceeded most often in August, and generally in samples with high chlorophyll concentrations. About two-thirds of the samples had chlorophyll concentrations above the severe nuisance level (30 ug/L), and more than 40 percent exceeded the WHO threshold of 50 ug/L.

Hypolimnetic Dissolved Oxygen and Lake Trophic Condition

In a stratified lake with predominantly surface outflow, the hypolimnion is the final destination of much of the organic matter produced by the resident algal community. As the organic matter decomposes in the hypolimnion, it consumes oxygen. The supply of oxygen in the hypolimnion is finite, having been "locked in" since stratification began and cut off from resupply via the atmosphere.

Because the supply of oxygen in the hypolimnion is finite, it can be exhausted if oxygen demand is high and prolonged. From the standpoint of aquatic life, it is of interest to know if enough dissolved oxygen (DO) will remain by the end of stratification. Several factors enter into the calculation:

1) the starting mass of oxygen (=volume*concentration), which is usually high because the water is usually quite cold when stratification begins
2) the rate of depletion, which is a function of the rate at which organic matter is supplied (which in turn is related to the abundance of algae)
3) the duration of stratification

Release of water from the bottom, as would be customary in most reservoirs, adds a few wrinkles because the volume of the hypolimnion (and thus the mass of oxygen) is likely to decrease, and the temperature is likely to increase. Both factors will tend to hasten the depletion of DO.

These processes could be modeled in a formal way, but that would be more appropriate where a site-specific standard is contemplated. The approach taken here is simpler and intended to facilitate a comparison across a set of lakes as a way of providing an additional line of evidence regarding water quality impacts of algal abundance.

Stratification and Depth

The focus for this evaluation is the extent to which trophic state is an important determinant of dissolved oxygen concentration in the hypolimnion of a stratified lake. To the extent that the hypolimnion serves at fish habitat, oxygen concentration is of greater interest in Cold lakes than Warm lakes. Some salmonids will use, or be restricted to, deep water habitat during the summer because that is the region of the lake offering suitable temperatures. Warm water fishes are more likely to find suitable habitat in shallow water.

For comparisons among lakes to be meaningful, it is necessary to restrict attention to those lakes that stratify, preferably without interruption during the summer months. This restriction is important because it ensures that deep water oxygen concentrations are not affected by exchange with the atmosphere. To a large extent, the likelihood of persistent stratification is determined by the depth of the lake.

An indicator of the strength of stratification, and thus also of persistence, is the difference in temperature between the top and bottom of the lake. For a cross-section of Cold lakes, the range of temperatures observed in mid-summer profiles is clearly related to depth (Figure 59). The range is large – usually at least 8°C – for deep lakes, and it diminishes sharply for lakes less than 10 or 20 meters deep. Broad experience with Colorado lakes suggests that persistent stratification is expected for lakes deeper than about 10 meters and unlikely for those shallower than about 5 meters.

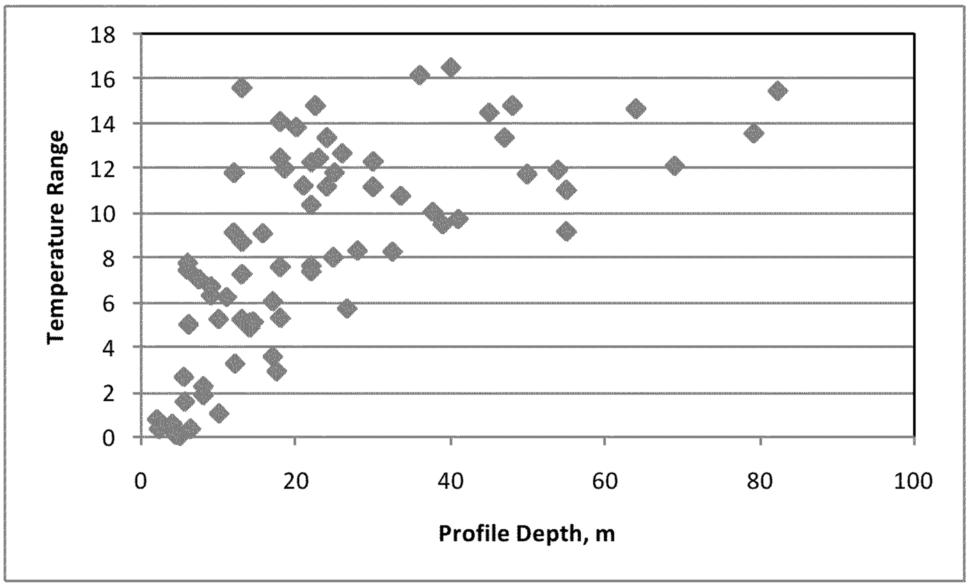

Figure 59. Range of temperatures as a function of profile depth for Cold lakes in mid -summer. The range is the difference between the maximum and minimum temperatures for all depths in the profil e except the one nearest the surface. The near surface temperature is excluded to avoid heat slicks that may form under calm conditions during daylight hours. Profiles taken between July 15 and August 15 represent mid -summer conditions.

For many of the lakes included in this study, mid-summer profiles are available for more than one year. In order to avoid over-representation of well-studied lakes, only one profile is included from each lake. In general, the analysis is based on the most recent profile from mid-summer (15 July to 15 August). When multiple profiles are available from mid-summer, preference is given to the one taken nearest to 1 August.

Determination of Hypolimnetic D.O. Concentration

The DO concentration in the hypolimnion – in contrast to the mixed layer – usually decreases with depth, raising a question about how to choose a representative concentration for comparison with other lakes. Neither the average nor the minimum is particularly meaningful from a biological perspective, but the median can be useful. When samples are taken at equally-spaced intervals, and the DO declines or remains constant with depth, the median DO concentration is located approximately at the mid-point of depth within the layer.

Locating the mid-point depth of the hypolimnion is more difficult than it sounds because the top of the layer is often poorly defined, especially in reservoirs where operations may “smear” the boundary between the adjacent layers. The problem of locating the upper boundary of the hypolimnion can be addressed by locating the thermocline[63] instead. Thus, the median hypolimnetic DO corresponds to the concentration observed at a depth halfway between the thermocline and the bottom. Half of the vertical distance and more than half of the volume in the hypolimnion will have DO concentrations greater than the median. In general, Cold lakes deeper than about 20 meters tend to have relatively high DO in the hypolimnion (Figure 60). Shallower lakes show more variation.

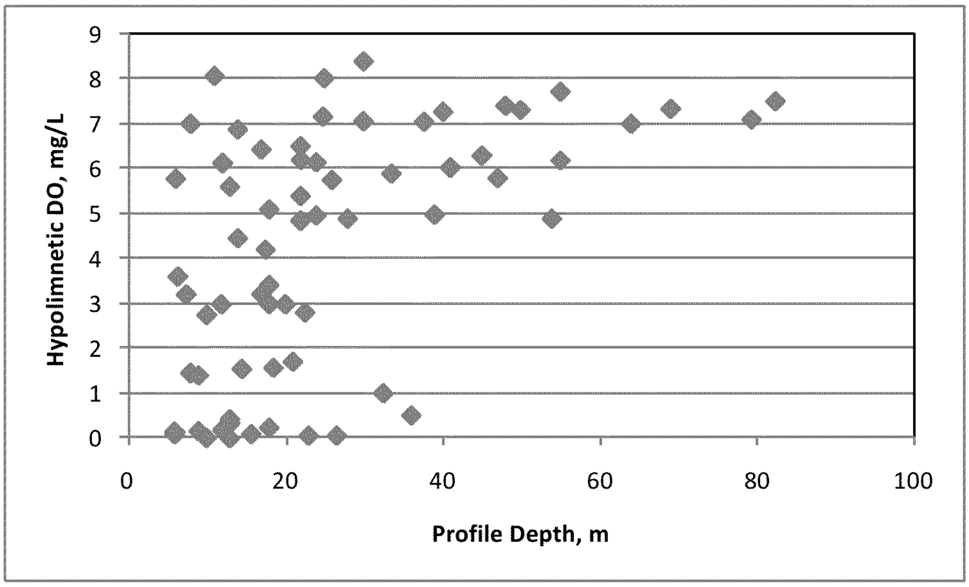

Figure 60. Hypolimnetic DO concentration as a function of profile depth for lakes assessed in mid -summer.

The association of depth and DO depletion is logical insofar as deeper lakes will tend to have a larger hypolimnetic volume and thus be able to assimilate a larger load of organic matter. However, it is not yet apparent whether the association is supported by a depth-related trend in trophic condition. One way to disentangle depth and productivity is to compare hypolimnetic DO for different trophic conditions in a set of lakes with similar depth.

The Role of Trophic Condition

For many of the lakes for which the profile data were assessed above, data are available for characterizing trophic condition. Most of the Cold lakes can be classified as oligotrophic or mesotrophic; more productive Cold lakes are not common in Colorado. The oligotrophic lakes maintain relatively high DO in the hypolimnion, but the shallower (10-40 meters) mesotrophic lakes may not (Figure 61). Although oxygen depletion is a real possibility in the shallower mesotrophic lakes, it seems unlikely in the mesotrophic lakes deeper than about 40 meters. The more productive lakes – eutrophic and hyper-eutrophic – tend to be shallower and maintain little DO in the hypolimnion.

[63] The thermocline is defined as “the plane of maximum rate of decrease of temperature with respect to depth” (Wetzel 2001). It lies within the metalimnion and is easier to locate than the boundary between the metalimnion and the hypolimnion.

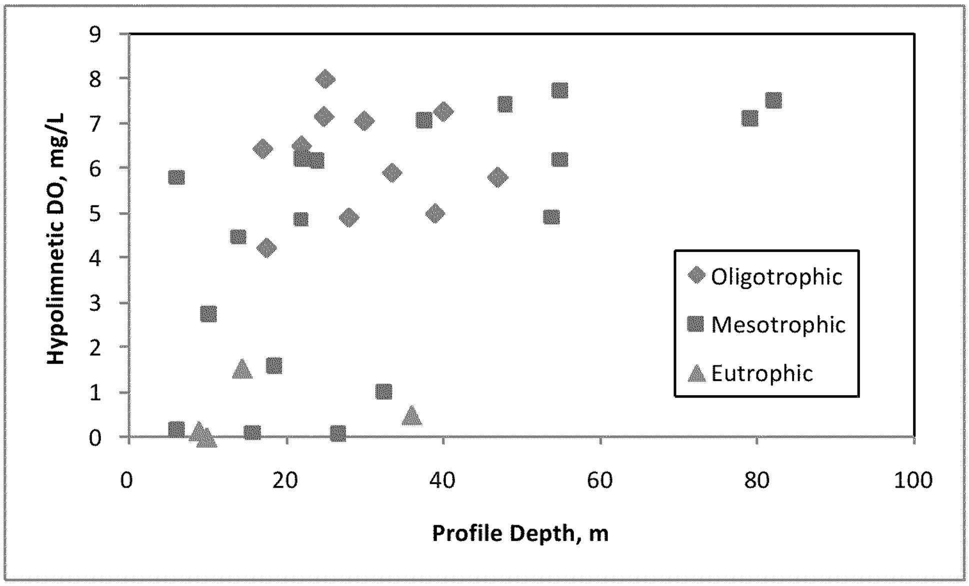

Figure 61. Hypolimnetic DO concentration as a function of profile depth for lakes assessed in mid-summer. The method for determining hypolimnetic DO is explained in the text. Lakes are segregated according to trophic condition; the eutrophic category includes one hyper-eutrophic lake.

The relationship between hypolimnetic DO and trophic condition confirms the qualitative expectation that, other things being equal, more productive lakes are more likely to show significant DO depletion in deep water. The relationship is presented qualitatively because it is not the basis for proposing criteria; it is simply a way of capturing the water quality impacts of increasing algal abundance.

Water Quality Impact Summary

Water quality can be diminished or even impaired when algae become too abundant. The impacts are not due to chlorophyll, which is simply a non-toxic indicator of algal abundance, but are due instead to algal demand for inorganic carbon (elevated pH), physical presence of algal cells (clarity, bloom formation), or compounds produced by algae (taste-and-odor, toxins). Linking these impacts to chlorophyll, even in an approximate way, is useful for evaluating policy options.

When algae are very abundant and growing rapidly, their demand for inorganic carbon can exceed re-supply from the atmosphere. The result is elevated pH. In Cold and Warm lakes, exceedance of the pH standard is likely when chlorophyll exceeds about 16 ug/L. The risk of elevated pH is associated mainly with Warm lakes, which tend to have higher chlorophyll levels than Cold lakes. However, the Division does not advocate using nutrient criteria as a means of *assuring* that the pH standard is attained. Instead, the Division recommends setting the chlorophyll criterion such that pH exceedances are not expected frequently.

Algal cells form part of the particulate matter suspended in lake water. As algal abundance increases, those cells block more light, reducing the clarity of the water. When chlorophyll levels approach 30 ug/L, clarity is reduced to about one meter, which seems to be the limit of what is acceptable[64]. A Secchi depth of 1.0 m also is a mid-range value for minimum Secchi depths in eutrophic lakes (OECD 1982).

High chlorophyll concentrations also are likely to be objectionable on aesthetic grounds. A user perception study of Texas reservoirs found that the average chlorophyll associated with "enjoyment … substantially reduced" was about 27 ug/L (TWCA 2005). A similar study in Florida placed the threshold at about 30 ug/L (Hoyer et al. 2004). A concentration of 30 ug/L also is the threshold for a "severe nuisance bloom". The frequency of severe nuisance blooms increases rapidly after the summer average concentration of chlorophyll exceeds about 15 ug/L.

Clarity and bloom frequency are important for perceptions of water quality. The Division is not proposing criteria for clarity or blooms, but the importance of perceptions should be acknowledged. Accordingly, it would be difficult to support a chlorophyll criterion above 20 ug/L (summer average) because bloom frequency would be excessive.

High algal abundance, especially in Warm lakes, tends to be accompanied by an algal community that is dominated by Cyanobacteria. An abundance of Cyanobacteria is undesirable for a variety of reasons, not least of which is their capacity to produce toxins. The risk of toxins can be minimized if individual chlorophyll measurements do not exceed 50 ug/L, and this is unlikely if summer average concentrations stay below about 20 ug/L.

It is important to emphasize that the relationships between chlorophyll concentration and water quality impacts are lines of evidence that helps establish a perspective on the relative merits of different proposals for criteria. The evidence suggests that when summer average concentrations exceed about 20 ug/L, several types of water quality impacts can be expected. This evidence helps establish an upper bound, but leaves open the question of whether a lower criterion is desirable from a policy perspective.

8. Defining Trophic Condition

The Division's proposal for nutrient criteria in lakes aims to establish a balance between potentially competing interests, while maintaining support for classified uses. The notion of establishing a balance implies an explicit and transparent role for policy-making at the state level. The more conventional approach, which defines nutrient criteria in order to protect reference conditions, incorporates policy-making differently.

The two approaches rely on fundamentally different goals for evaluating use protection, as explained in "*Policy and the Approach to Nutrient Criteria Development*". The reference approach aims, as a matter of policy, for what is "natural and attainable" for lakes in a region. The implicit assumption is that uses are protected in a natural setting, and that anything less is not good enough.

[64] This conclusion was reached in a recent review in support of criteria development in Virginia; AAC_Addendum2_2005, http://www.deq.virginia.gov/wqs/rule.html#NUT2

As a matter of practice, reference conditions typically are defined with a distributional analysis that yields "least impacted" or "most attainable" conditions. The outcome is that a functional implementation of reference (as "most attainable", for example) is one step removed from the rationale for use protection. Alternatively, it could be argued that use protection can still be attained with conditions that are less than pristine.

States that develop nutrient criteria by the reference approach have accepted implicitly a position that leaves little latitude for policy-making. Implementation of the reference approach, whether the distributional analysis is applied to pristine lakes or to the best available lakes, sets an upper bound for nutrients. Any option for less restrictive criteria, but still protective of uses, is foreclosed.

The Division's recommendation of target trophic conditions aims at what provides an acceptable balance of interests while still protecting uses. The policy is defined at the state level, and it places use protection first. There are no implicit assumptions equating "best available" with use protection. In addition, there are no assumptions about what percent of lakes must be impaired, as would be the case when the distributional approach is used. The Division's approach provides flexibility from a policy-making perspective because the Commission can evaluate the tradeoffs – the operational aspects of balancing interests – that can be explored from a policy perspective.

Lakes differ considerably in their capacity to support algal abundance. The range of algal abundance is usually divided into three primary categories, or trophic states, from low to high chlorophyll concentration: oligotrophic, mesotrophic, and eutrophic. Of course, there is really a continuum of algal abundance, but classification makes it easier to generalize about other attributes, including water quality and fishery yield, on the basis of lake productivity.

Trophic state boundaries are largely the product of expert opinions about lake productivity and the related biological and water quality characteristics. Several schemes have been proposed, and these were explored previously in "*Eutrophication: Process and Problem*". The Division recommends the OECD classification of trophic condition (Table 18). Reliance on the OECD classification is partly for convenience, but the generalizations also must make sense in terms of conditions found in Colorado lakes. Based in part on analysis of water quality impacts (see "*Algal Abundance and Water Quality Impacts*"), the Division chose the OECD.

Trophic State	Chlorophyll, ug/L	Total Phosphorus, ug/L	Secchi, m
Oligotrophic	1 – 2.5	4 – 10	12 – 6
Mesotrophic	2.5 – 8	10 – 35	6 – 3
Eutrophic	8 – 25	35 – 100	3 – 1.5
Hyper-eutrophic	>25	>100	<1.5

Table 18. OECD boundaries for trophic states in terms of chlorophyll, total phosphorus and Secchi depth.

Target Trophic Conditions

The Division uses "trophic condition" to describe the long-term, or persistent, characteristics of a lake. As long as there is no significant trend that involves an increase or decrease in nutrient loading, trophic condition does not change. Of course, chlorophyll and nutrient concentrations will vary within a season and among years, but the expression of natural variability does not alter the trophic condition of the lake. Trophic condition is the typical level of productivity over the long term, and it changes only when there has been a significant change in nutrient loadings.

Target trophic conditions have been identified for Cold and Warm lakes in Colorado (see "*Policy and the Approach to Nutrient Criteria Development*"). In general, Cold lakes should be at the lower end of the productivity range (mesotrophic or less). The OECD boundary between mesotrophic and eutrophic conditions – 8 ug/L – is chosen as the upper bound for summer average chlorophyll concentration. In a previous section ("*Algal Abundance and Water Quality Impacts*"), the target trophic condition for Cold lakes appears to achieve the desired balance in the sense that there was little risk of jeopardizing use protection from the standpoint of other criteria like pH.

Warm lakes can be, but are not required to be, more productive (eutrophic or less) than Cold Lakes. Setting the target trophic condition at eutrophic for Warm lakes should be consistent with a healthy, productive warm water fishery. The OECD boundary between eutrophic and hyper-eutrophic is 25 ug/L. However, when the chlorophyll threshold in Warm lakes is set to 25 ug/L, there is an increased risk of elevated pH, diminished clarity, bloom frequency, and the abundance of Cyanobacteria (see "*Algal Abundance and Water Quality Impacts*").

Reducing the threshold to 20 ug/L, for summer average chlorophyll in Warm lakes, does much to reduce the level of risk. Bloom frequency is cut in half and the frequency of Secchi depths less than 1.0 meter is reduced by one-third. Also, the frequency with which summer pH exceeds 9.0 is reduced below 15 percent. Thus, the proposal was amended[65] to shift the target trophic condition for Warm lakes to a point well within the eutrophic range.

Developing Criteria Consistent with Target Trophic Conditions

The proposed chlorophyll thresholds provide the point of departure for defining chlorophyll criteria. The missing component is the exceedance frequency. The Division recommends allowing one exceedance in five years. The basis for an assessment would be the set of summer average chlorophyll concentrations available for each listing cycle. Once in five years, one summer average for chlorophyll could exceed 8 ug/L in a Cold lake or 20 ug/L in a Warm lake; these are the numeric criteria proposed for chlorophyll in lakes. Setting the exceedance frequency to once in five years is consistent with recent adoptions by the Commission.

The chlorophyll criteria were proposed to ensure that trophic condition did not exceed the target level. Criteria also are proposed for phosphorus and nitrogen, and the Division is recommending that those criteria be established on the basis of algal response relationships developed for Colorado lakes.

[65] The Division's proposal for Warm lakes has evolved over the years. The original proposal in 2009 set the threshold to 20 ug/L, based in part on a preliminary evaluation of fishery quality. Later, when the trophic condition concept became the basis for criteria development, eutrophic conditionswere viewed as supportive of warm water fisheries and the draft value was increased to 25 ug/L to be consistent with the upper boundary of eutrophic conditions. A thorough evaluation of the water quality implications has shown the shortcomings of 25 ug/L, leading to the present proposal of 20 ug/L.

The algal response relationship between chlorophyll and phosphorus (or nitrogen) is described in "*Nutrients and Algal Abundance*". Ordinary least squares regression is used to define the best fit of the relationship for paired summer average concentrations. These response relationships are the appropriate basis for linking chlorophyll and phosphorus (or nitrogen) concentrations associated with the central tendency, or long-term value, that characterizes each target trophic condition. Exceedance thresholds are based on "translators" derived separately from the distributions of each of the three constituents – chlorophyll, phosphorus, and nitrogen.

Translators

For each target trophic condition, there is a typical level of algal abundance that is the long-term average or the median (50th percentile) of summer average concentrations from many years (i.e., the distribution). The median, or typical value, is the most secure basis for linking chlorophyll to nutrients with the algal response relationships.

For a lake that exactly matches the target trophic condition, the most important characteristic of the distribution of summer average values is the 80th percentile – the summer average concentration that can be exceeded once in five years (i.e., 8 ug/L for Cold lakes and 20 ug/L for Warm lakes). A "translator" is needed to determine the median of a distribution that has a particular value – 8 or 20 for the 80th percentile.

Translator development relies on a set of well-studied Colorado lakes. To qualify, a lake must have a record consisting of summer average chlorophyll concentrations from at least five years, and each average must be based on at least three samples taken in the same summer. It is assumed that these lakes are not experiencing any significant trends in nutrient loading.[66] The data sets consist of 23 lakes for chlorophyll, 24 lakes for phosphorus, and 13 lakes for nitrogen.

The distribution is assumed to be lognormal, and the mean and standard deviation of log-transformed values are calculated. A statistical function[67] in Excel is used to determine the back-transformed values for the 50th (median) and 80th percentiles. Plots of the derived percentiles for chlorophyll show a strong relationship (Figure 62). The exceedance values for chlorophyll are about 50 percent larger than the central tendency. Thus, central tendency for a Cold lake that exactly matches the target trophic condition would be 5.25 ug/L, and the comparable value for a Warm lake would be 12.94 ug/L.

[66] Bear Creek Reservoir is an exception. Strict effluent limitations were imposed for phosphorus following adoption of the control regulation in 1992, resulting in a significant reduction in phosphorus loading to the reservoir. Consequently, data for this reservoir prior to 1996 were not included in the analysis. No comparable changes in loading are known for the other reservoirs.

[67] The LOGINV function "returns the inverse of the lognormal cumulative distribution function of x, where ln(x) is normally distributed with parameters mean and standard deviation."

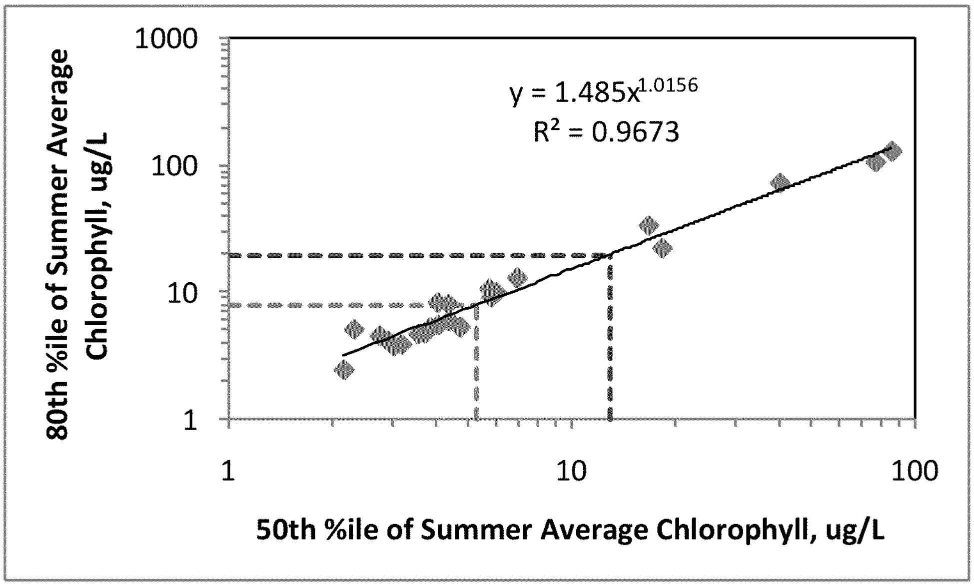

Figure 62. Translation between central tendency and exceedance threshold for summer average concentrations of chlorophyll in ug/L. Analysis is based on distributions derived from 23 well-studies lakes. Dashed lines show example translations corresponding to the upper bound of mesotrophic conditions (8 ug/L) and the upper bound of eutrophic conditions (20 ug/L).

Development of translators for phosphorus and nitrogen operates on the same principles outlined for chlorophyll, but starting from the other end of the relationship. Rather than starting with the exceedance threshold, the starting value for phosphorus and nitrogen is central tendency, which is derived from the algal response relationships presented in *"Nutrients and Algal Abundance"*. The summer average concentration of phosphorus that corresponds to the target trophic condition proposed for Cold lakes (typical summer average chlorophyll of 5.25 ug/L) is 0.020 mg/L. The comparable phosphorus number for Warm lakes (summer average chlorophyll of 12.94 ug/L) is 0.066 mg/L.

As mentioned previously, chlorophyll and phosphorus are linked on the basis of typical values for each target trophic condition. For Cold lakes, these values are 5.25 ug/L chlorophyll and 0.020 mg/L phosphorus. The criterion value for phosphorus must be determined with a translator function that defines the 80th percentile based on the 50th percentiles (Figure 63). The exceedance threshold for phosphorus is about twenty percent larger than the central tendency. When the translator function is applied to the typical summer average phosphorus concentrations of 0.020 mg/L for Cold lakes and 0.066 mg/L for Warm lakes, the resulting exceedance thresholds are 0.025 and 0.083 mg/L, respectively.

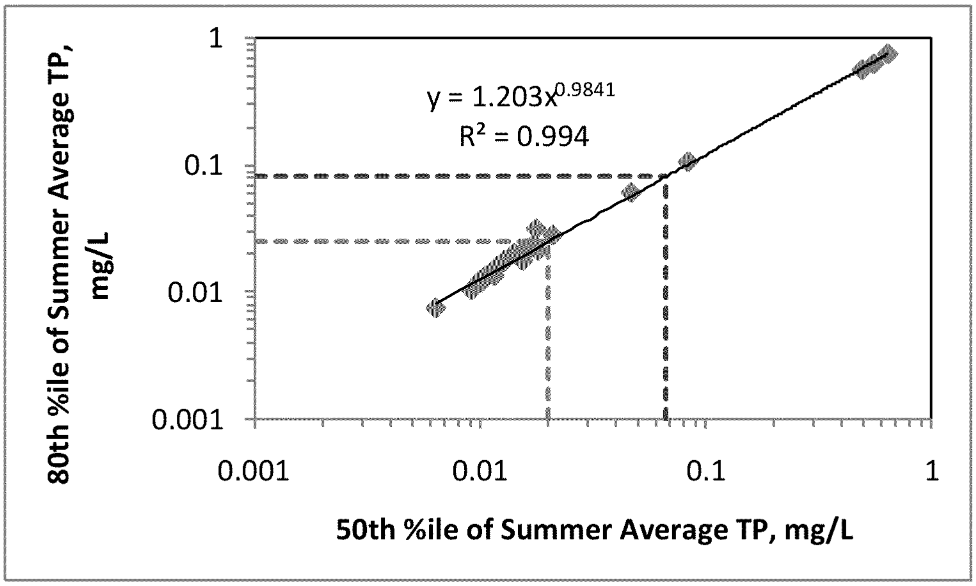

Figure 63. Translation between central tendency and exceedance threshold for summer average concentrations of total phosphorus. Analysis is based on distributions derived from 24 well-studies lakes. See text for further explanation. Dashed lines show example translations corresponding to the upper bound of mesotrophic conditions (0.025 mg/L) and the upper bound of eutrophic conditions (0.083 mg/L).

The same logic is applied to summer average concentrations of total nitrogen. The summer average concentration of nitrogen that corresponds to the target trophic condition proposed for Cold lakes is 0.358 mg/L. The comparable nitrogen number for Warm lakes (summer average chlorophyll of 12.94 ug/L) is 0.744 mg/L. The exceedance threshold for nitrogen is about one-fourth larger than the central tendency (Figure 64). When the translator function is applied to the typical summer average nitrogen concentrations, the exceedance thresholds would be 0.426 and 0.910 mg/L, respectively.

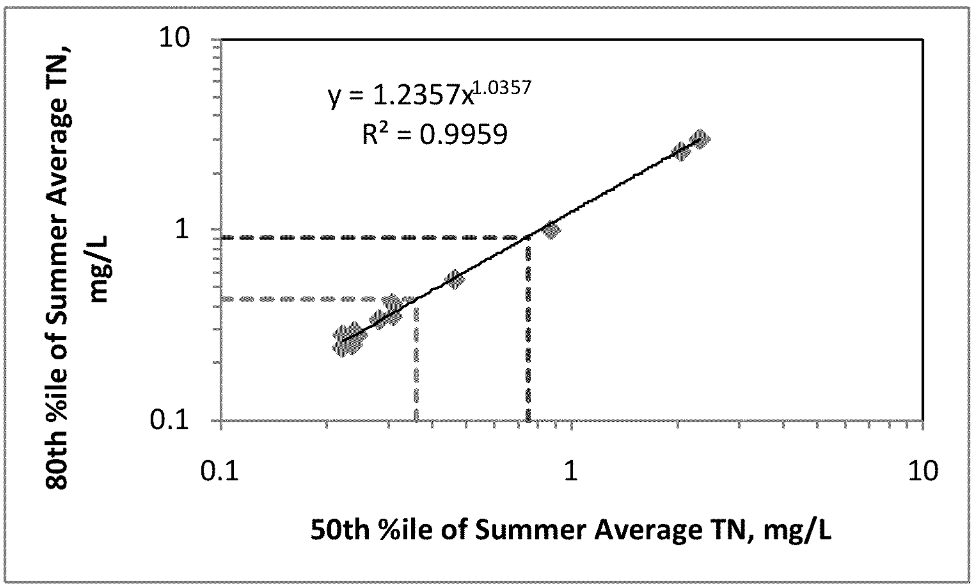

Figure 64. Translation between central tendency and exceedance threshold for summer average concentrations of total nitrogen. Analysis is based on distributions derived from 13 well-studies lakes. See text for further explanation. Dashed

lines show example translations corresponding to the upper bound of mesotrophic conditions (0.426 mg/L) and the upper bound of eutrophic conditions (0.910 mg/L).

Forecasting Water Quality Implications of Target Trophic Condition

The concept of trophic condition conveys useful generalizations about water quality conditions and potential fishery yield, for example, but it is not sufficient alone for anticipating the full range of water quality impacts. In large part, this shortcoming is unavoidable because some water quality impacts, like elevated pH, are associated with instantaneous levels of algal abundance (i.e., grab samples) rather than average levels. Fortunately, as shown in "*Characterizing Algal Abundance*", it is possible to predict the range of grab sample values for chlorophyll based on the summer average concentration for a given lake.

The ability to forecast the distribution of chlorophyll values associated with a particular summer average concentration broadens the value of the trophic condition concept. Generalizations about water quality and fishery yield can be augmented by information about the probability of blooms or pH exceedances, for example. Much is known about the variability of chlorophyll during the summer and the variability of the summer averages across years. Those two facets of variability have been quantified for Colorado lakes and can be used to make forecasts that helps describe the water quality implications of different proposals for target trophic condition.

In particular, the capacity to incorporate year-to-year variability in a realistic manner removes the need to rely on the [incorrect] assumption that all years are the same, and that all water quality impacts are as serious as if the chlorophyll concentration were routinely at the level of the criterion. By definition, a lake that matches the target trophic condition will have summer average chlorophyll concentrations below the criterion in four out of five years. In those years, even in Warm lakes, pH values above 9.0 are less likely than they would be in a year when the summer average equals the criterion.

Both facets of variation – within season and among years – can be incorporated in forecasts of grab sample values. In general, an assessment of summer average chlorophyll concentration would be based on data from a five-year interval within which one exceedance is allowed. By defining seasonal and interannual patterns of variation, reasonable forecasts of the distribution of grab sample chlorophyll concentrations can be developed for a five-year period.

The statistical basis for the modeling framework was presented in "*Characterizing Algal Abundance*". The relationship between the average and the standard deviation of summer chlorophyll concentrations makes it possible to describe the distribution of grab sample concentrations associated with any average value. A similar relationship was developed for summer averages, making it possible to define the variability associated with any target trophic condition.

When the two elements of variation – seasonal and interannual – are united in a modeling framework, it becomes possible to evaluate trade-offs between reduced transparency and increased fishery yield, for example. Although neither transparency nor fishery yield is constrained by a standard, both are important from a policy perspective. One might ask how often the Secchi depth – a conventional measure of transparency – would be reduced to 1.0 meter or less, and this could be forecast on the basis of the distribution of grab sample values for chlorophyll.

Modeling Framework

The model creates frequency distributions of summer chlorophyll concentrations based on a Colorado-specific relationship between the average and the standard deviation. An example is constructed for a scenario in which the summer average concentration is 6.0 ug/L (Figure 65). The distribution of grab sample values is presented as exceedance frequencies; a concentration of 1.7 ug/L would be exceeded at all times, and a concentration of 7.3 ug/L would be exceeded about 25% of the time.

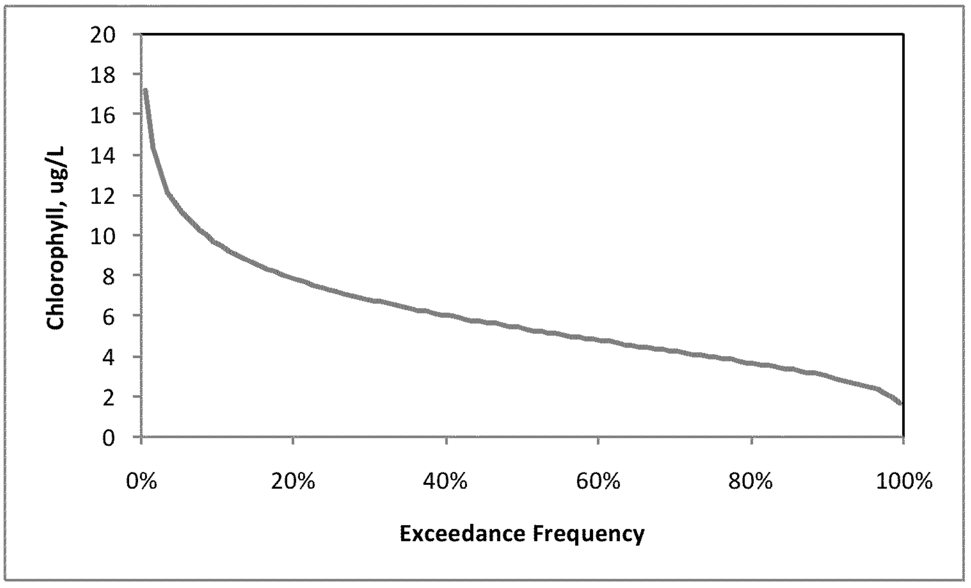

Figure 65. Exceedance frequencies predicted for summer chlorophyll concentrations (grab samples) in a summer with an average concentration of 6.0 ug/L.

A similar approach is taken to generate a frequency distribution of summer average concentrations based on a target trophic condition that is mesotrophic (Figure 66). This example corresponds to the Division's proposal for Cold lakes, for which the typical summer average would be 5.7 ug/L. The distribution of summer average concentrations is presented as exceedance frequencies; an average concentration of 2 ug/L would be exceeded at all times, and an average concentration of 7.5 ug/L would be exceeded about 25% of the time.

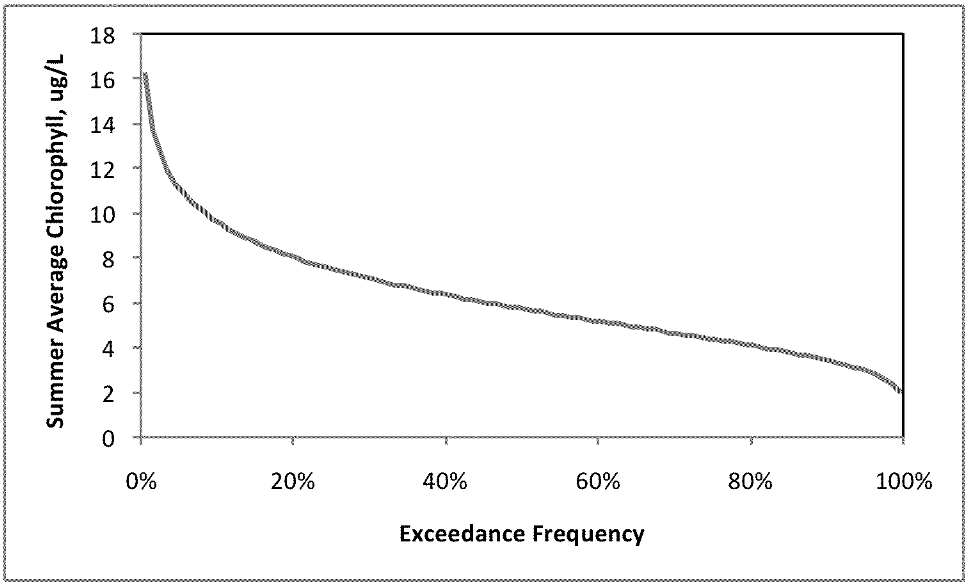

Figure 66. Exceedance frequencies predicted for summer average chlorophyll concentrations consistent with a target trophic state of mesotrophic.

The two figures with exceedance frequencies show two "slices" from the broader model framework, which represents the "universe" of individual chlorophyll values expected if a lake matching the target trophic condition were sampled indefinitely. The starting point for the model is the typical summer average concentration corresponding to a proposed target trophic state. The framework consists of a 100-by-100 matrix in which rows are summer averages and columns are grab sample concentrations (Table 19).

Each row represents the set of summer measurements generated from the summer average shown in column 2 of the table. Each cell in the row contains a grab sample concentration corresponding to a specific percentile in the distribution. There are 100 cells structured to show values at 1 percent intervals beginning at 0.5 percent and continuing through 99.5 percent[68]. One row was the basis for Figure 65.

The column containing the set of summer averages is generated in the same way. Each cell in the column contains a summer average concentration corresponding to a specific percentile in the distribution. There are 100 cells structured to show values at 1 percent intervals beginning at 0.5 percent and continuing through 99.5 percent. This column was the basis for Figure 66.

Summer Average Chlorophyll		**Summer Chlorophyll Concentrations (ug/L) Corresponding to Percentiles from Distribution for Each Summer Average**						
Percentile	**Value (ug/L)**	**0.005**	**0.015**	**0.025**	**...**	**0.975**	**0.985**	**0.995**

[68] The 1 percent increments are produced with the LOGINV function in EXCEL™ using the long-term average (or the summer average) and the corresponding standard deviation as defined previously in this section. The arguments for the LOGINV function are the mean and standard deviation of the log-transformed data. Relationships between arithmetic and log-transformed moments are taken from Aitchison & Brown, as presented in Walker (1985); see also Gilbert (1987).

Summer Average Chlorophyll		Summer Chlorophyll Concentrations (ug/L) Corresponding to Percentiles from Distribution for Each Summer Average						
Percentile	**Value (ug/L)**	**0.005**	**0.015**	**0.025**	**...**	**0.975**	**0.985**	**0.995**
0.5	2.0	0.7	0.8	0.9		3.9	4.2	4.8
1.5	2.4	0.8	1.0	1.1		4.6	5.0	5.9
2.5	2.6	0.9	1.0	1.1		5.1	5.5	6.5
...								
97.5	12.7	2.9	3.6	4.0		30.5	34.0	42.0
98.5	13.8	3.1	3.8	4.3		33.6	37.6	46.5
99.5	16.2	3.5	4.3	4.9		40.5	45.4	56.6

Table 19. Structure of spreadsheet used to link the frequency distribution for summer average chlorophyll concentrations to the frequency distribution for individual values within each summer. In this example, the target trophic condition is set to be mesotrophic or less, for which the criterion value is 8 ug/L. Each row represents a percentile from the distribution of summer averages. Percentiles in the first column are ordered and at fixed intervals of 1 percent (starting at 0.5 percent). Only the first three and last three percentiles are shown. The summer averages corresponding to each percentile are shown in the second column. The remaining columns show chlorophyll concentrations expected from the distribution of grab sample values. The structure of the columns also is ordered and at 1 percent intervals.

The purpose of the modeling exercise is to improve the basis for understanding the trade-offs when selecting among policy options that strike different balances among competing interests. It is not intended as a mechanism for guaranteeing that a particular trophic condition is preserved or that the pH standard is never exceeded, but it is useful for minimizing risks. The same modeling framework is used for evaluating options for criteria in Cold and Warm lakes, but different target trophic conditions are considered.

Three kinds of water quality impacts are considered in the analysis – bloom frequency, pH exceedances and diminished transparency. Other potential impacts, such as hypolimnetic DO and changes in fish community composition cannot be quantified at this time. Expectations for each impact can be specified for each cell in the 100-by-100 matrix of output from the forecasting model.

Cold Lakes

The Division proposes a criterion value of 8 ug/L for summer average chlorophyll in Cold lakes. The intent is to keep Cold lakes in the mesotrophic or oligotrophic categories. The criterion value can be exceeded once in five years (i.e., it is the 80th percentile of the distribution of summer average concentrations).

When a lake is attaining the proposed chlorophyll criterion for Cold lakes, summer average concentrations typically remain well within the mesotrophic range (2.5 – 8 ug/L). Under these conditions, algal blooms would not be expected (Table 20). There is always a statistical probability of a bloom, but it is too small to be of practical interest. A single bloom in excess of 30 ug/L could accompany a once in 10 year event (i.e., a summer with a 90th percentile average chlorophyll concentration), but there is essentially no chance of a 50 ug/L bloom in a lake in attainment of the Cold criterion.

Parameter	Cold Lakes	Warm Lakes	
80th Percentile Summer Average Chlorophyll, ug/L	8.0	20.0	
Blooms >30 ug/L, typical days per summer	0	4	

Parameter	Cold Lakes	Warm Lakes	
Blooms >50 ug/L, typical days per summer	0	0	
pH Excursions, typical days per summer	3	13	
Transparency <1.0 meter, typical days per summer	0	19	
Transparency <2.0 meters, typical days per summer	5	91	

Table 20. Expectations for chlorophyll concentration and related water quality parameters based on criterion values proposed for Cold and Warm lakes. See text for explanation of statistical basis. Entries for da ys per summer are calculated from percentages produced by the forecasting model and applied to a summer season of 92 days. Some rounding was necessary.

The chance of exceeding the pH standard, for Cold lakes in attainment of the chlorophyll criterion, is quite small. In a typical summer, only about 3 percent (3 of 92 days) of the individual pH values would exceed 9.0, and this is much less than would constitute an exceedance. Similarly, Secchi depths would always exceed 1.0 meter and would exceed 2 meters most of the time.

Warm Lakes

For Warm lakes, the proposed criterion value would be set at 20 ug/L, with a once-in-five-year exceedance frequency. Blooms would occur on about 4 days each summer and an exceedance of the pH standard is possible, although chiefly in more extreme years (Table 20). Secchi depth would typically exceed 1.0 meter.

Lake Criteria Summary

The Division's proposal for numeric nutrient criteria is built around the concept of a target trophic condition. The intent of the concept is to achieve a balance among potentially competing interests while protecting uses. Seeking a balance of interests implies an explicit and transparent policy role.

The Division recommends *mesotrophic*, or less productive, as the target trophic condition for Cold lakes because it is optimal for a trout fishery. Maintaining a healthy fishery indicates support for the aquatic life use and satisfies one facet of recreational interest. Aesthetic interests, which are another facet of recreation, also are likely to be satisfied by water clarity. Water quality problems such as elevated pH or bloom formation are not expected. A mesotrophic, or less productive, condition is attained if the summer average chlorophyll concentration does not exceed 8 ug/L. Lakes that exceed 8 ug/L have become more productive than the target trophic condition.

The Division recommends *eutrophic* as the target trophic condition for Warm lakes because it is the optimal for warm water fisheries. Although the fishery in a eutrophic lake may satisfy one recreational interest, evaluation of water quality information revealed that the uppermost range of eutrophic conditions will not strike an acceptable balance of interests or provide adequate protection of uses. Water quality problems become evident when summer average chlorophyll concentrations exceed about 20 ug/L. A modest reduction (to 20 ug/L from 25 ug/L) of the upper boundary of eutrophic conditions reduces the risk of exceedances of the pH standard (high algal abundance can be responsible for raising the pH) and provides an acceptable balance of interests. Accordingly, the Division proposes a chlorophyll threshold of 20 ug/L for Warm lakes.

Linking response (chlorophyll) and causal (nitrogen and phosphorus) variables is based on central tendency for each target trophic condition, and the numeric values are derived from algal response relationships. Central tendency for chlorophyll is determined with a translator developed using data from Colorado lakes (Table 21). Central tendency for chlorophyll is linked to central tendency for nitrogen and phosphorus using algal response relationships. These values provide a good characterization of what is typical for each target trophic condition.

	Chlorophyll (ug/L)	Total Phosphorus (ug/L)	Total Nitrogen (ug/L)
Cold Lakes	5.3	20	358
Warm Lakes	12.9	66	744

Table 21. Typical summer average concentrations of chlorophyll, phosphorus and nitrogen in lakes at the upper boundary of the target trophic conditions.

Separate translators for nitrogen and phosphorus, also derived from Colorado lake data, are used to determine the exceedance thresholds associated with each nutrient. The complete set of criteria, each based on a summer average concentration with a once-in-five-year exceedance frequency, is shown in Table **22**.

	Chlorophyll (ug/L)	Total Phosphorus (ug/L)	Total Nitrogen (ug/L)
Cold Lakes	8	25	426
Warm Lakes	20	83	910

Table 22. Criteria proposed for chlorophyll, phosphorus and nitrogen concentrations in lakes meeting target trophic conditions.

The Division believes the proposed numeric criteria provide an acceptable balance of interests without creating unacceptable risk to other aspects of water quality. At the same time, other water quality standards – for DO and pH – serve as a backstop for situations where the proposed nutrient criteria may miss the mark. This degree of flexibility is both possible and desirable because of the non-toxic nature of the pollutants in question.

9. Context for Criteria Development

Development of nutrient criteria presents significant technical and policy challenges that many states have attempted to confront. Criteria development is mandated, but states are allowed considerable latitude in selecting an approach, provided that it is scientifically defensible. The flexibility for developing an approach is appropriate and necessary given the variability in local or regional conditions that shape expectations for nutrient conditions in each state.

EPA has provided guidance in the form of ambient water quality recommendations (i.e., 304a criteria) that recognize the linkage between lakes and the surrounding landscape. Lakes in similar ecological regions – ecoregions – are likely to experience similar nutrient conditions. Where sufficient data are available in an ecoregion, the causal and response variables related to nutrient criteria development can be characterized. States can choose to nutrient criteria based on the ecoregion concept or to develop alternative criteria by a different, scientifically-defensible approach.

When states take a different approach, there is generally a significant investment of effort in the technical analyses intended to make the approach scientifically-defensible. Colorado is fortunate in that it is not the first state to undertake these technical analyses. Consequently, there is an opportunity to benefit from the technical approaches and insights available in documentation of criteria development by other states.

An overview of nutrient criteria proposed or adopted by other states provides context for the Division's proposals. Direct comparisons may even be appropriate in cases where the basis for use protection is similar. The intent is to find common ground on technical issues and to compare conclusions reached regarding the technical basis for protection.

EPA's Recommendations for Nutrient Criteria

EPA's recommendations for nutrient criteria were based on analysis of available information in 12 of the 14 aggregated nutrient ecoregions (Table 23). The recommendations are based on a distributional approach that equates the upper bound of "reference" conditions with the 25th percentile of all measured values.[69] States may adopt the recommended values or develop their own criteria using scientifically defensible approaches. Most states have opted to pursue alternative approaches.

Aggregate Nutrient Ecoregion	TP, mg/L	TN, mg/L	Chl a, µg/L	Secchi, m
I. Willamette and Central Valleys				
II. Western Forested Mountains*	0.009	0.10	1.9	4.50
III. Xeric West*	0.017	0.40	3.4	2.70
IV. Great Plains Grass and Shrublands*	0.020	0.44	2.0	2.00
V. South Central Cultivated Great Plains*	0.033	0.56	2.3	1.30
VI. Corn Belt and Northern Great Plains	0.038	0.78	8.6	1.36
VII. Mostly Glaciated Dairy Region	0.015	0.66	2.6	3.33
VIII. Nutrient Poor Largely Glaciated Upper Midwest and Northeast	0.008	0.24	2.4	4.93
IX. Southeastern Temperate Forested Plains and Hills	0.020	0.36	4.9	1.53
X. Texas-Louisiana Coastal and Mississippi Alluvial Plains				
XI. Central and Eastern Forested Uplands	0.008	0.46	2.8	2.86
XII. Southeastern Coastal Plain	0.010	0.52	2.6	2.10
XIII. Southern Florida Coastal Plain	0.018	1.27	12.4	0.79
XIV. Eastern Coastal Plain	0.008	0.32	2.9	4.50

Table 23. Recommended numeric nutrient criteria for lakes and reservoirs in each of the aggregate nutrient ecoregions; developed by US EPA. Those ecoregions marked with an asterisk (*) are represented in Colorado; taken from http://www.epa.gov/waterscience/criteria/nutrient/ecoregions/files/sumtable.pdf

EPA's recommendations for total phosphorus are low and fall in a surprisingly narrow range – 0.008 to 0.038 mg/L. Recommendations for total nitrogen are more variable, but, with one exception, all are less than 0.8 mg/L. Recommendations for algal abundance (chlorophyll concentration) are extremely low (1.2 – 2.4 ug/L), which would imply that all Colorado lakes should be oligotrophic. Recommendations

[69] See EPA website for the approach and details related to each ecoregion: http://water.epa.gov/scitech/swguidance/waterquality/standards/criteria/aqlife/pollutants/nutrient/ecoregions_lakes_index.cfm

for transparency (Secchi depth) are, not surprisingly, inversely related to the corresponding values for chlorophyll; high algal abundance results in low transparency.

Most of EPA's criteria documents also include recommendations applicable to geographic sub-units (Level 3 Ecoregions) of each aggregated nutrient ecoregion. There are six level 3 ecoregions in Colorado, and the relevant criteria documents provide recommended criteria for each (Table 24). In general, the variation among the recommendations for level 3 ecoregion in Colorado is considerably less than the variation among the nutrient ecoregions across the country.

Level 3 Ecoregion	TP, mg/L	TN, mg/L	Chl a, ug/L	Secchi, m
18: Wyoming Basin	0.010	0.38 (C)	1.4	3.0
21: Southern Rockies	0.015	0.88	1.7	4.2
20: Colorado Plateaus	0.003	0.15 (C)	1.4	3.2
22: Arizona/New Mexico Plateau	0.015	0.31	2.0	2.9
25: Western High Plains	0.024	0.50 (C)	2.4	1.5
26: Southwestern Tablelands	0.020	0.39 (C)	1.2	1.7

Table 24. Recommended numeric nutrient criteria for lakes and reservoirs in each of the level 3 ecoregions represented in Colorado. Total nitrogen criteria are taken from the "reported" values unless otherwise noted (C="calculated'). Chlorophyll criteria are taken from the spectrophotometric method.

Criteria Adopted or Proposed by States

At least 27 states have some form of numeric nutrient criteria for lakes, although the nature of the criteria varies among the states. Like Colorado, some states are still in the development process. A few states have applied criteria statewide (e.g., Rhode Island), but most apply criteria to specific categories of lakes.

The basis for classifying lakes is an important part of the criteria development process because it helps shape water quality expectations, especially where a reference approach is taken. The link between watershed characteristics and water quality, for example, is implicit in categorizations based on the ecoregion concept. Existing uses also could provide a basis for categorization based on prior policy decisions concerning uses. Another logical basis for partitioning lakes might be the distinction between natural lakes and man-made reservoirs.

Some states define categories according to ecoregion (e.g., South Carolina, Washington), classified use (e.g., New Jersey, Nevada), or fishery type (e.g., North Carolina, West Virginia). Other states use more elaborate schemes involving cross-classification. Virginia uses ecoregion and fishery type, Arizona uses lake type and designated use, and Minnesota uses ecoregion and use. Finally, there are a few states that appear to have taken an exclusively site-specific approach (e.g., Alabama and Texas).

The information presented for individual states is drawn from various sources including state regulations, listing methodologies, and postings to state and EPA websites. Numeric values may have been proposed or adopted, or they may represent thresholds used for listing or for implementation of a narrative. While each may have a different legal interpretation, they all convey valuable technical judgments about protection of uses.

South Carolina

South Carolina has adopted numeric nutrient criteria for lakes classified according to ecoregion (Table 25). No distinction is made between natural lakes and reservoirs, but virtually all lakes in South Carolina are reservoirs. The numeric criteria are applied to lakes with surface area of at least 40 acres; smaller lakes are covered by the narrative standard (South Carolina Department of Health and Environmental Control [SCDHEC] 2004). Waters in the Blue Ridge ecoregion support trout. Assessment is based on the 75th percentile of the available measurements.

Ecoregion	Chlorophyll (ug/L)	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)
Blue Ridge Mountains	10	0.02	0.35
Piedmont and Southeastern Plains	40	0.06	1.50
Middle Atlantic Coastal Plains	40	0.09	1.50

Table 25. Numeric criteria adopted for lakes of different ecoregions in South Carolina. The criteria are 75th percentile values for chlorophyll (ug/L), total phosphorus (mg/L), and total nitrogen (mg/L).

Minnesota

One of the most thoroughly documented examples of lake nutrient criteria development comes from Minnesota, which has developed criteria in a manner that accounts for ecoregion and use (Table 26). Ecoregion plays an important role in developing expectations about trophic status; for example, lakes in the Corn Belt are expected to be more eutrophic than lakes in the Northern Forests. The criteria also acknowledge that lakes supporting natural populations of lake trout require special protection based on the deep-water oxygen requirements for this species.

Class	Lake Type	Ecoregion	Chlorophyll ug/L	Total P mg/L	Secchi m
2A	Lake Trout Lakes[70]	All	3	0.012	4.8
2A	Trout Lakes	All	6	0.020	2.5
2Bd, 2B	Lakes, Shallow Lakes, and Reservoirs	Northern Lakes & Forests	9	0.030	2.0
2Bd, 2B	Lakes and Reservoirs	North Central Hardwood Forest	14	0.040	1.4
2Bd, 2B	Lakes and Reservoirs	Western Corn Belt & Northern Glaciated Plains	22	0.065	0.9
2Bd, 2B	Class 2Bd, Shallow Lakes	North Central Hardwood Forest	20	0.060	1.0
2Bd, 2B	Class 2Bd, Shallow Lakes	Western Corn Belt & Northern Glaciated Plains	30	0.090	0.7

Table 26. Eutrophication standards adopted by Minnesota for lakes and reservoirs. Chlorophyll (ug/L), total phosphorus (mg/L), and Secchi (m) standards are compared to summer (Jun-Sep) averages. A lake is considered impaired when the total phosphorus standard and either the chlorophyll or Secchi standards are not met (MPCA 2009). The Secchi standard is not met if the measured depth is less than the table value.

Minnesota has established definitions for distinguishing between lakes, shallow lakes, and reservoirs (Minnesota Pollution Control Agency [MPCA] 2009). To qualify, a water body must be 10 acres or larger and have a hydraulic residence time of at least 14 days. Shallow lakes have a maximum depth of not more than 15 feet, or at least 80 percent of the lake is "shallow enough to support emergent and

[70] Supporting natural populations of lake trout

submerged rooted aquatic plants". The guidance recognizes that in some instances, judgment will have to be used to decide if the water body is a shallow lake, lake, or wetland. Reservoirs are distinguished from lakes mainly by having artificial control of the outflow.

The same eutrophication standards are applied to lakes and reservoirs classified as 2B or 2Bd. However, the guidance document acknowledges that site-specific modifications may be necessary to "account for characteristics of reservoirs that can affect trophic status, such as water temperature, variations in hydraulic residence time, watershed size, and the fact that reservoirs may receive drainage from more than one ecoregion." Shallow lakes are treated the same as lakes and reservoirs in one, but not all ecoregions.

Assessment is based on the average of all summer (June-September) data available from the most recent 10-year period. A lake is considered impaired when the total phosphorus standard and either the chlorophyll or Secchi standards are not met (MPCA 2009). For comparison among states, the MN approach yields the equivalent of a long-term average concentration.

Virginia

Virginia has adopted a classification scheme that is similar to that of Minnesota in that it relies on ecoregion and use (specifically the fishery type; Table 27). The classification scheme is used to apply nutrient criteria to man-made lakes and reservoirs that are included in Section 187[71]; the two natural lakes are covered by site-specific standards.

Ecoregion	Fishery Type	Chlorophyll (ug/L), 90th percentile	Chlorophyll (ug/L), median	Total Phosphorus (mg/L), median
9	Cool	25	10	0.030
9	Warm	35	25	0.040
9	Fertilized	60	60	0.040
11	Cold	10	4	0.010
11	Cool	25	10	0.020
11	Warm	35	25	0.040
14	Cool	25	10	0.020
14	Warm	60	25	0.040

Table 27. Nutrient criteria adopted by Virginia for man-made lakes and reservoirs. The 90th percentile of chlorophyll (ug/L) and the median total phosphorus (mg/L) are calculated with data from the assessment period, which extends from April through October. Applies to Section 187 waters; for lakes not included in Section 187, other criteria are used.

Assessment of Section 187 lakes is based on the 90th percentile of chlorophyll concentrations and the median total phosphorus concentration (VaDEQ 2010). "The aquatic life (fishery) use of the entire water body listed in Section 187 is considered impaired for nutrients if the criterion for either chlorophyll a or total phosphorus is exceeded in each of the two most recent monitoring years." When there has been documented use of algicide (e.g., copper sulfate), only the total phosphorus data is assessed.

[71] See 9 VAC 25-260-187 Virginia Water Quality Standards for the complete list containing 121 lakes. In general, a lake on this list is larger than 100 acres, has public access, and is a managed fishery.

Virginia assesses on a six-year cycle in which a lake is normally sampled during one year. If the chlorophyll standard is exceeded, sampling is extended to include a second year. A violation is registered if the second year also shows an exceedance.

The exceedance frequency is not stated explicitly, but, for the purpose of translating the Virginia chlorophyll criterion to a common basis for comparison with Colorado's proposed values (see below), it is assumed that the Virginia criterion represents the 90th percentile in a median year. No attempt is made to replicate the conditional nature of the Virginia assessment methodology – involving chlorophyll and/or phosphorus.

Arizona

Arizona is developing nutrient criteria based on designated use and four categories of lake type. The uses include Aquatic and Wildlife for warm, cold, and effluent-dependent waters (A&Ww, A&Wc, A&Wedw), Full-Body and Partial-Body Contact (FBC and PBC), and Domestic Water Source (DWS). Lake categories include deep lakes and reservoirs (average depth >18 ft), shallow lakes (average depth <3 meters; maximum depth <4 meters), urban lakes, and lakes in igneous or sedimentary watersheds. No distinction is made between lakes and reservoirs for the purpose of evaluating attainment.

A narrative has been developed by the Arizona Department of Environmental Quality (ADEQ 2008). The narrative is an elaboration of the "free-from" approach: "A surface water shall not contain pollutants in amounts or combinations that …*c+ause the growth of algae or aquatic plants that inhibit or prohibit the habitation, growth, or propagation of other aquatic life or that impair recreational uses." It is not being used for listing until implementation procedures are adopted. The most recent version of water quality standards[72] includes the narrative and the implementation procedures, but EPA has not yet completed its review of the regulations.

Attainment of the narrative is determined through a tiered system of decisions based on target numeric values for individual constituents (Table 28). When the seasonal average chlorophyll is less than the lower target value in the table (e.g., less than 5 ug/L for A&Wc lakes), the standard is attained; when it exceeds the upper target (e.g., greater than 50 ug/L for A&Wedw lakes), it is not in attainment. When the seasonal average falls within the target range (e.g., 10-20 ug/L for DWS lakes), then the narrative is attained only if three other criteria are met:

1) The mean blue green algae count is at or below 20,000 per milliliter, and
2) The blue green algae count is less than 50 percent of the total algae count, and
3) There is no evidence of nutrient-related impairments such as:
    a. An exceedance of dissolved oxygen or pH standards
    b. A fish kill coincident with a dissolved oxygen or pH exceedance
    c. A fish kill or other aquatic organism mortality coincident with algal toxicity
    d. Secchi depth is less than the lower value prescribed for the lake and reservoir category
    e. A nuisance algal bloom is present in the limnetic portion of the lake or reservoir

[72] Title 18: Environmental Quality, Chapter 11: Department of Environmental Quality, Article 1: Water Quality Standards; effective March 25, 2009.

f. The concentration of total phosphorous, total nitrogen, or total Kjeldahl nitrogen is greater than the upper value in the range prescribed for the lake and reservoir category.

Use	Lake Category	Chlorophyll (ug/L)	Secchi (meters)	Total Phosphorus (mg/L)	Total Nitrogen (mg/L)	Total Kjeldahl Nitrogen (mg/L)
FBC&PBC	Deep	10-15	1.5-2.5	0.070-0.090	1.2-1.4	1.0-1.1
FBC&PBC	Shallow	10-15	1.5-2.5	0.070-0.090	1.2-1.4	1.0-1.1
FBC&PBC	Igneous	20-30	0.5-1.0	0.100-0.125	1.5-1.7	1.2-1.4
FBC&PBC	Sedimentary	20-30	1.5-2.0	0.100-0.125	1.5-1.7	1.2-1.4
FBC&PBC	Urban	20-30	0.5-1.0	0.100-0.125	1.5-1.7	1.2-1.4
A&Wc	All	5-15	1.5-2.0	0.050-0.090	1.0-1.4	0.7-1.1
A&Ww	Urban	30-50	0.7-1.0	0.125-0.160	1.7-1.9	1.4-1.7
A&Ww	Other	25-40	0.8-1.0	0.115-0.140	1.6-1.8	1.3-1.6
A&Wedw	All	30-50	0.7-1.0	0.125-0.160	1.7-1.9	1.4-1.7
DWS	All	10-20	0.5-1.5	0.070-0.100	1.2-1.5	1.0-1.2

Table 28. Numeric targets for lakes and reservoirs in Arizona. Lakes are classified according to use, and type category (see text). Averages during the peak season of productivity (April - October for warm lakes; May - September for cold lakes). Concentrations for nitrogen and phosphorus are shown as mg/L; chlorophyll is ug/L; Secchi depth is in meters.

Lakes are assessed on the basis of peak season means where at least two samples must be available to calculate each mean. An impairment decision requires "a minimum of two violations … within a five-year assessment period." Primary decision criteria are based on chlorophyll, and decisions are conclusive only if chlorophyll is below the lower bound or above the upper bound. There is a broad range within which chlorophyll alone is not conclusive. For the purpose of facilitating translation to a common basis, the upper and lower bounds are treated as once-in-five-year exceedance thresholds (i.e., 80th percentiles of the peak season mean distribution).

Wisconsin

Wisconsin proposed phosphorus criteria for 8 lake categories. In addition, some standards had already been established through the Great Lakes Water Quality Agreement. The categories partition lakes according to hydrology, depth, and fishery type (Wisconsin Department of Natural Resources [WDNR] 2009). Lakes smaller than 10 acres are not yet subject to numeric criteria.

Larger lakes are separated first according to stratification status[73] – shallow (mixed) and deep (stratified). Lakes can be further separated on the basis of hydrology into seepage lakes that have no defined surface inflow or outflow and drainage lakes that have surface inflow and/or outflow. In addition, there are three kinds of lakes representing particular natural communities – 1) spring ponds that are usually small, spring-fed, coldwater systems that support trout, 2) two-story fishery lakes that are deep enough to stratify and can support coldwater species in the hypolimnion, and 3) impoundments created by dams. The impoundments are further classified on the basis of hydraulic residence time during the summer months. If the residence time is less than 14 days, the water body is considered an "impoundment" and is assessed under the assessment methodology for rivers and

[73] WDNR uses the Lillie/Lathrop equation to predict stratification status (WDNR 2009). The equation is a function of maximum depth and lake surface area.

streams. If the residence time is at least 14 days, it is considered a "reservoir" and assessed along with natural lakes.

The WDNR board approved phosphorus criteria in June 2010, and the rules were scheduled to go into effect in 2011. The intent of the phosphorus criteria is to ensure that nuisance algal blooms (>20 ug/L) occur infrequently (less than one week per summer, June-September).[74] The criteria are compared to summer median concentrations (May-October), and there is an allowable exceedance frequency of once in three years (Table 29). Although reservoirs are assigned to separate categories, they are assessed with the same criteria values applied to lakes.

Lake Type	Total Phosphorus, mg/L
Lake Superior open and nearshore waters	0.005
Lake Michigan open and nearshore waters	0.007
Stratified "two-story" fishery lakes	0.015
Stratified seepage lakes	0.020
Stratified drainage lakes	0.030
Stratified reservoirs	0.030
Non-stratified (shallow) drainage lakes	0.040
Non-stratified (shallow) lakes	0.040
Non-stratified reservoirs	0.040
Impoundments	Same as inflowing river or stream

Table 29. Numeric criteria for total phosphorus (mg/L) in Wisconsin lakes. See text for explanation of lake typology.

Kansas

Kansas has developed a relatively simple classification scheme: "All lakes managed by federal, state, county, or municipal entities and those private lakes and reservoirs used for public drinking water supply or open to the general public for secondary contact recreation, are classified lakes and reservoirs, a portion of those lakes and reservoirs are listed in the Kansas Surface Water Register." Chlorophyll concentration alone is the basis for use support in Kansas lakes (Kansas Department of Health and Environment [KDHE] 2010). Numeric thresholds are used to interpret the narrative standard, and different thresholds apply to different uses. The threshold for full support of the aquatic life use is 18 ug/L, which is calculated as the average of all available values. For the purpose of comparisons, the threshold is interpreted as a long-term average.

Florida

Nutrient criteria have been proposed by U.S. EPA for lakes in Florida. Criteria were developed for three categories of lakes. Those categories separate colored lakes (>40 platinum cobalt units [PCU]) from clear lakes (<=40 PCU), and further partition the clear lakes into alkaline (>20 mg/L as $CaCO_3$) and acidic (<=20 mg/L as $CaCO_3$) groups based on alkalinity (Table 30).

Each chlorophyll criterion is compared to the annual geometric mean and may not be exceeded more than once in three years. In addition, the long-term average of annual geometric means may not exceed

[74] Notice of Public Hearings WT-25-08; http://dnr.wi.gov/org/water/wm/wqs/phosphorus/phos_hrg_notice.pdf; accessed September 2010.

the criterion value. In addition to the chlorophyll and baseline nutrient criteria, there are "modified bounds" for nutrients. The modified bounds set a range within which lake-specific total phosphorus and total nitrogen values can be derived provided that the chlorophyll criterion is met.

Lake Category	Chlorophyll (ug/L)	Baseline Total Phosphorus (mg/L)	Baseline Total Nitrogen (mg/L)	Total Phosphorus Modified Criteria (mg/l)	Total Nitrogen Modified Criteria (mg/L)
Colored	20	0.050	1.27	0.05-0.16	1.27-2.23
Clear, alkaline	20	0.030	1.05	0.03-0.09	1.05-1.91
Clear, acidic	6	0.010	0.51	0.01-0.03	0.51-0.93

Table 30. Numeric nutrient criteria for chlorophyll (ug/L) and nutrients (mg/L) proposed by EPA for Florida lakes. See text for description of lake categories and explanation of modified criteria.
http://water.epa.gov/lawsregs/rulesregs/upload/floridaprepub.pdf

To facilitate comparison with other states, the median is assumed to be equivalent to the geometric mean; this is a logical assumption when the data are lognormally distributed. The exceedance frequency – once in three years – corresponds to the 67th percentile of the set of summer medians.

Other States

West Virginia makes no distinction between natural lakes and reservoirs. The state has adopted nutrient criteria for lakes, but some aspects remain under review by EPA. The classification scheme is simple, consisting of cool lakes[75] and warm lakes. Criteria are specified as seasonal averages for chlorophyll and total phosphorus (Table 31). The table shows proposed revisions that have not yet been adopted; the adopted criteria were 15 ug/L and 30 ug/L for chlorophyll and 0.030 mg/L and 0.050 mg/L for total phosphorus in cool and warm lakes, respectively, but these were not approved by EPA. Impairment decisions would be based on seasonal mean (May-October) chlorophyll concentration. It is not clear what exceedance frequency is allowed.

State	Lake Type	Chl (ug/L)	TP (mg/L)	TN (mg/L)	Basis	Season	Comment
WV	Cool	10	0.030		Average	May-Oct	Revised proposal
WV	Warm	20	0.040		Average	May-Oct	Revised proposal
OR	Natural, stratified	10			Average		
OR	Natural, not stratified; Reservoirs	15			Average		
WA	Coast Range Puget Lowlands Northern Rockies		0.020				Trigger Level
WA	Cascades		0.010				Trigger Level
WA	Columbia Basin		0.035				Trigger Level

[75] "*Cool water lakes* are lakes managed by the West Virginia Division of Natural Resources for cool water fisheries, with summer residence times greater than 14 days." Warm lakes are all others. (West Virginia Department of Environmental Protection, Water Resources: Title 47 – Series 2 – Requirements Governing Water Quality Standards). The definition of cool lakes and the nutrient criteria for lakes are still under review by EPA.

State	Lake Type	Chl (ug/L)	TP (mg/L)	TN (mg/L)	Basis	Season	Comment
NC	Class C, trout	15			90th percentile from 5-y assessment period		
NC	Class C, no trout (Mountains and Upper Piedmont)	25			90th percentile from 5-y assessment period		Proposed addition to standards
NC	Class C, no trout	40			90th percentile from 5-y assessment period		
IA	All	25			75th percentile	May-Sep	Proposed

Table 31. Nutrient criteria and thresholds for lakes in North Carolina, Oregon, Washington, and West Virginia.

Oregon has adopted chlorophyll criteria for two categories of lakes – natural lakes that stratify, and natural lakes that do not stratify plus reservoirs (Table 31). Ponds and reservoirs less than 10 acres are excluded, as are saline lakes.

Washington is in the process of developing nutrient criteria and has proposed “action levels” for total phosphorus in some, but not all, ecoregions in the state (Table 31). When the ambient phosphorus concentration exceeds the action level, a “lake specific study may be initiated.” Expected ranges of total phosphorus are based on the trophic states found in the different ecoregions.

North Carolina has adopted chlorophyll criteria for two classes of lakes – those designated as trout waters and those that are not (Table 31). They are presently in the process of adopting a new chlorophyll criterion of 25 ug/L that would apply to non-trout waters in the Mountains and Upper Piedmont regions. The criteria apply to all lakes and reservoirs of at least 10 acres. The assessment period is five years, and evaluation of the criterion is based on the 90th percentile of all data.

Iowa is proposing criteria that would apply to all lakes and reservoirs that have a mean depth of at least three meters (“deep” lakes according to Iowa’s documentation). In addition to the chlorophyll criterion, there would be a transparency criterion requiring that 75% of the measurements be one meter or more. Previously, lakes were evaluated on the basis of TSI values; if the TSI exceeded 65, the lake was not meeting the narrative criteria (Iowa DNR 2009).

In addition to the states that have been featured in the foregoing, there are 16 others that have nutrient criteria or thresholds, and more that are in development (e.g., New Mexico and Colorado).

Colorado Site-specific Nutrient Criteria

Colorado has not yet adopted numeric nutrient criteria for lakes, but site-specific criteria have been adopted in five lakes (Table 3). Four of the five lakes are subject to control regulations which have been in place for many years. Consequently, the Division and stakeholders have had considerable experience with the issues associated with establishing the necessary controls in the watersheds. Two lakes for which criteria were adopted originally in narrative form now have numeric criteria. An important motivator for changing to numeric criteria was the difficulty of evaluating the narratives.

Lake	TP Criterion (mg/L)	Chlorophyll Criterion (ug/L)	Adopted	Comment
Bear Creek	Narrative		1992	Intended to reverse eutrophication and return trophic state to mesotrophic - eutrophic boundary
Bear Creek	0.032	10	2009	Acknowledges that internal loading, which is a legacy effect of historical eutrophication, will delay prospects for attainment
Chatfield	0.027	17[76]	1984	Hold as close to historical trophic state as possible
Chatfield	0.030	10	2009	Reaffirms commitment to preserve historical trophic state, and adjusts standard to better reflect those conditions
Cherry Creek	0.035	15[77]	1984	Hold as close to historical trophic state as possible
Cherry Creek	0.040[78]	15	2000	
Cherry Creek		18	2009	
Dillon	0.0074		1984	Preserve 1982 trophic state
Standley	Narrative			Maintain as mesotrophic
Standley		4.0	2009	Concern about drinking water quality

Table 32. Site-specific nutrient criteria adopted for Colorado reservoirs.

Generalizations about Lake Criteria

Many states have proposed or adopted nutrient criteria or thresholds for protection of beneficial uses. Chlorophyll and total phosphorus are the constituents included most often, but several states also have criteria for nitrogen or transparency (Secchi depth). The criteria vary among states in terms of classification schemes, basis for assessment (e.g., averages vs. percentiles), and types of aquatic life that may be covered. Direct comparisons are difficult, however, because the numeric values do not have a common basis.

Adjustment to a common basis is necessary before comparing the magnitudes of the criteria under the same conditions for frequency and duration. Some criteria are based on percentiles and some are averages; some aggregate all available data and some focus attention on a specific season. The Division chose long-term average as a common basis for comparing criteria among states. The translations are made using output from the model described in "*Defining Trophic Condition*", which generates distributions for grab sample concentrations linked to a distribution of yearly values consistent with a pre-selected long-term value. Translations are approximate because the model is derived exclusively from Colorado data and because assumptions were sometimes required concerning assessment procedures of other states. Nevertheless, an approximate translation is preferable to making direct comparisons of criteria with disparate bases.

Several states have criteria that are aimed at protection of cold water aquatic life, chiefly through a focus on salmonid fisheries (Table 33). Although the basis for assessment varies among the states, several common features emerge clearly. Protection of cold water aquatic life requires low levels of

[76] Goal
[77] Goal
[78] Goal

algal abundance – typically in the mesotrophic range or lower – and low nutrient concentrations are necessary to maintain low algal abundance. When put on a common basis, chlorophyll criteria range from 3 to 11 ug/L, and the Division's proposal falls in the middle of the range.

State	Lake Type	Chlorophyll Criterion (ug/L)	Common Basis Chlorophyll (ug/L)	Original Basis for Assessment
MN	Lake Trout	3	3	Average of all summer values
MN	Trout	6	6	Average of all summer values
VA	Cold Water Fishery	10	6.7	90th percentile each season
AZ	A&W cold	5-15	3.9-11.4	80th percentile of peak season means
SC	Blue Ridge	10	8.1	75th percentile of all summer grab samples
NC	Trout	15	8.2	90th percentile of grab samples
CO	**Cold**	**8**	**6.2**	**80th percentile of summer avgs**

Table 33. Chlorophyll concentrations associated with protection of cold-water aquatic life. The original basis for assessment varies among states. A separate column shows an approximate translation of the original chlorophyll criteria to a common basis, which is the underlying long-term average. The proposed criterion for cold water lakes in Colorado is shown for perspective.

For several states, it was possible to link the numeric criteria with intent to support non-salmonid fisheries (Table 34). The range of chlorophyll concentrations is large compared to that encountered for salmonid fisheries (Table 33). In part, the breadth expected because of the diversity of fish species, with different tolerances, that are managed in the different states. Despite the broad range of values, the criteria generally suggest that encouraging hyper-eutrophic conditions is not desirable for fishery support.

State	Lake Type	Chlorophyll Criterion (ug/L)	Common Basis Chlorophyll (ug/L)	Basis
AZ	A&Ww urban	25-40	18.9-30.0	80th percentile of peak season means
AZ	A&Ww other	30-50	22.6-37.3	80th percentile of peak season means
MN[79]	NLF	9	9	Average of all summer values
MN	CHF deep	14	14	Average of all summer values
MN	CHF shallow	20	20	Average of all summer values
NC	Non-trout, Mountains and Upper Piedmont[80]	25	13.2	90th percentile of grab samples
NC	Other non-trout	40	20.7	90th percentile of grab samples
SC	Mid-Atlantic Coastal Plain	40	32.7	75th percentile of summer grab samples
SC	Piedmont & SE Plains	40	32.7	75th percentile of summer grab

[79] Minnesota classifies non-trout lakes according to ecoregion and depth. In general, lakes of the Northern Lakes & Forests (NLF) ecoregion are managed for cool water fisheries (induding walleye) and the those of the Central Hardwood Forest (CHF) ecoregion are managed for warm water fishes (including panfish and bass). The other two ecoregions are managed for warm water fishes, but are generally too enriched to sustain the fish through the winter without aeration; the predominant fish often are carp and other rough fish (MPCA 2005).
[80] In process of being adopted according to NCDENR staff. Presently, all non-trout waters are covered by the 40 ug/L standard.

State	Lake Type	Chlorophyll Criterion (ug/L)	Common Basis Chlorophyll (ug/L)	Basis
				samples
VA	Ecoregion 9, Cool water	25	16.1	90th percentile each season
VA	Ecoregions 11 & 14, Cool water	25	16.1	90th percentile each season
VA	Ecoregion 9 & 11, Warm water	35	27.2	90th percentile each season
VA	Ecoregions 14, Warm water	60	37.3	90th percentile each season
CO	**Warm**	**20**	**15.2**	**80th percentile of summer avgs**

Table 34. Nutrient criteria associated with protection of warm -water aquatic life. Concentrations of chlorophyll are in ug/L. The basis for assessment varies among states; see text for further explanation. Proposed criteria for warm water lakes in Colorado are shown for perspective.

The broad category of non-salmonid fisheries is often divided into "cool" and "warm" categories, and some states – like Virginia and Minnesota – have developed criteria that recognize the distinction explicitly. The two fishery categories differ in environmental preferences, especially for temperature (cool water fish prefer 18-25°C; warm water fish prefer temperatures in excess of 25°C). In general, cool water fisheries support species like crappie, walleye, and pike, whereas warm water fisheries support bass, bluegill, and "wiper". Rough fish like carp and bullheads also fall in the warm water category, but are tolerant of highly enriched conditions and not generally considered desirable as game fish.

The chlorophyll criterion proposed by the Division for Warm lakes in Colorado is near the lower end of values proposed or adopted for warm water fisheries by other states. In this respect, the Division's proposed criteria are more similar to the values that MN and VA have adopted for cool water fisheries. However, there is no reason to think that they are incompatible with support for a wiper fishery, for example. The higher levels of algal abundance that other states have found to be consistent with support for warm water fisheries would not be consistent with other facets of water quality in Colorado lakes.

Summary of Comparisons with Other States

States have taken a variety of approaches for development of nutrient criteria, resulting in considerable diversity in classification schemes and assessment procedures. Each approach builds on local knowledge of lake types and uses, and each approach reflects policy considerations specific to the state. A scheme tailored for Minnesota lakes, for example, is not necessarily appropriate for another state, but it does reveal a way of thinking about lakes that another state could use.

The classification scheme proposed by the Division is simple compared to most other states, but the simplicity is deceptive. The strong association of most environmental gradients with elevation means that fishery type and ecoregion are largely congruent in a way that would not happen in a plains state. The proposed scheme fits Colorado's geographic character, which has a mountain-plains dichotomy of aquatic habitats, and the existing separation of the Aquatic Life use into Cold and Warm categories.

The assessment procedure proposed by the Division relies on seasonal average concentrations. Several other states also use seasonal averages, although the length of the season varies among states. Exceedance frequencies also vary among states, with some, like Colorado, linking exceedances to the assessment cycle.

The diversity in classification schemes and assessment procedures that appears in the approaches taken by other states might lead one to expect a wide range of outcomes in terms of numeric criteria. However, this does not seem to be the case once comparisons are made on a common basis with respect to use protection and assessment of the data. In particular, chlorophyll criteria for protection of salmonid fisheries (cold water aquatic life) fall in a relatively narrow range, suggesting broad support for the technical conclusions reached by the Division. Even for the warm water fisheries, for which there is a broad range of chlorophyll criteria across the states, the technical conclusions are affirmed once differences within the fishery category are better understood.

Most of the Division's development of nutrient criteria has been undertaken in isolation in the sense that it involved state staff working with Colorado data. This overview of criteria development by other states has provided an opportunity to consider the merits of all technical aspects of the Division's proposal. In general, the Division's proposal is similar to criteria developed by other states to protect similar uses.

The overview also has helped the Division by highlighting two lake attributes – size and residence time – that could be incorporated to strengthen the proposal. As indicated in "*Description and Classification of Colorado Lakes*", there are many small ponds and lakes in the sub-alpine region of the state. Relatively little data are available for these lakes that are predominantly natural. The Division's proposal was strengthened by following the example set by several other states of setting a lower size boundary for lakes assessed against the numeric criteria.

The second improvement to the Division's proposal that was a direct result of having conducted this overview was the addition of a residence time requirement. Not many states have included a residence time requirement, but the logic is very compelling. It is fundamentally about making a distinction between a lake and a wide spot in a stream. If the water does not "reside" in a water body for long enough to develop plankton populations, for example, the habitat is more like a stream than a lake, at least from an ecological perspective.

A minimum residence time of fourteen days appears in regulations for a few states, and the Division agrees that this is a reasonable minimum for Colorado lakes. Water bodies with a shorter residence time will be assessed as streams.

10. Summary and Recommendations

Anthropogenic nutrient enrichment poses a serious threat to water quality in lakes. The threat to water quality exists on a national scale, and Colorado is no exception. In lakes, the primary problem caused by nutrient enrichment is excessive abundance of algae. When algae are excessively abundant, common water quality problems include elevated pH, depletion of dissolved oxygen, reduced water clarity, frequent formation of blooms, production of toxins, complaints about taste and odor in drinking water, and increased risk of disinfection by-products in drinking water. These problems are the result of excessive algal abundance, which is caused by nutrient enrichment.

Nutrient enrichment is not a new problem in Colorado. Concerns about actual or potential degradation of water quality in lakes have been brought before previous Commissions. Standards have been adopted and Control Regulations have been implemented on a limited, site-specific basis to maintain or improve water quality in affected lakes. Lakes for which regulations have been adopted include Chatfield Reservoir, Cherry Creek Reservoir, Bear Creek Lake, and Standley Lake in the Denver Metro area, and Lake Dillon in Summit County.

Nutrient-related water quality problems in Colorado extend beyond those lakes where regulations have been adopted. Additional lakes show symptoms of an over-abundant nutrient supply, as indicated by pH and dissolved oxygen problems sufficiently severe to warrant a place on the Impaired Waters or Monitoring and Evaluation Lists (in Regulation #93).

The Division recommends setting a policy goal based on lake productivity, or trophic condition. This is in contrast to EPA's recommended approach of selecting goals based "reference conditions." The problem with the reference approach is that use protection is defined implicitly and all lakes not meeting reference conditions are automatically impaired.

Trophic condition is really a continuum from low productivity (*oligotrophic*) to high productivity (*hyper-eutrophic*), and the continuum has been divided into a few trophic states for which there are some general expectations for water quality. The key is selecting the target levels of algal abundance that achieve a balance of potentially competing interests without jeopardizing protection of the use. For example, fishing interests may prefer a more productive lake (higher algal abundance) than swimming or boating, yet either interest could be protected without jeopardizing the use. Striking the proper balance is a matter of policy.

The Division recommends *mesotrophic*, or less productive, as the target trophic condition for Cold lakes. Mesotrophic is the optimal trophic condition for a trout fishery, and trout are typical of the biota expected in Cold lakes. Maintaining a healthy fishery is an indication of support for the aquatic life use, and it satisfies one facet of recreational interest. Water clarity is expected to be sufficient to satisfy another facet (aesthetics) of recreational interests. Water quality problems such as elevated pH or bloom formation are not expected either. A mesotrophic, or less productive, condition is attained if the summer average chlorophyll concentration does not exceed 8 ug/L. Lakes that exceed 8 ug/L have become more productive than the target trophic condition.

The Division recommends *eutrophic* as the target trophic condition for Warm lakes. Eutrophic is the optimal trophic condition for warm water fisheries. Careful evaluation of water quality information revealed that the uppermost range of eutrophic conditions will not strike an acceptable balance of interests or provide adequate protection of uses. However, a modest reduction of the upper boundary of eutrophic conditions reduces the risk of exceedances of the pH standard (high algal abundance can be responsible for raising the pH) and provides an acceptable balance of interests. Accordingly, the Division proposes a chlorophyll threshold of 20 ug/L for Warm lakes.

The recommendations for target trophic condition are based on a response variable (chlorophyll) and the associated expectations for water quality. The causal variables are the nutrients nitrogen and phosphorus. The Division recommends developing criteria for nitrogen and phosphorus. The inclusion of nitrogen is based on evidence of nitrogen limitation and nitrogen deficiency from lakes in Colorado and the surrounding region. In addition, the recommendation for control of nitrogen is supported by recent scientific literature, and nitrogen is included in the latest proposal for nutrient criteria in Florida.

The recommendations for nitrogen and phosphorus were developed with algal response relationships derived from Colorado lakes. The relationships were evaluated at central tendency for a lake that exactly matches the target trophic condition for Cold lakes or for Warm lakes (Table 35).

	Chlorophyll (ug/L)	Total Phosphorus (ug/L)	Total Nitrogen (ug/L)
Cold Lakes	5.3	20	358
Warm Lakes	12.9	66	744

Table 35. Central tendency for summer average concentrations of chlorophyll, phosphorus and nitrogen in lakes that are at the upper boundary of the target trophic condition for Cold lakes and Warm lakes.

The linkage between central tendency and exceedance threshold is a translator based on empirical mean-variance relationships for each constituent (Table **36**). The exceedance threshold is the summer average concentration that has an allowable exceedance frequency of once in five years. The computational sequence begins with the chlorophyll thresholds (8 and 20 ug/L) and uses the chlorophyll translator to derive central tendency (5.2 and 12.9 ug/L). Algal response relationships are used to calculate the phosphorus and nitrogen values corresponding to central tendency for chlorophyll. Finally, the phosphorus and nitrogen translators are used to calculate exceedance thresholds from central tendency.

	Chlorophyll (ug/L)	Total Phosphorus (ug/L)	Total Nitrogen (ug/L)
Cold Lakes	8	25	426
Warm Lakes	20	83	910

Table 36. Recommended criteria for chlorophyll, total phosphorus and total nitrogen concentrations for Cold and Warm lakes. Each criterion is the summer average (July 1 – September 30) in the mixed layer of lakes (median of multiple depths), allowable exceedance frequency 1-in-5 years.

In segments where numeric values are adopted, they would apply to lakes that are at least 25 acres in size and have a residence time of at least fourteen days. For lakes smaller than 25 acres, the narrative standard would be applied. Lakes with a residence time of less than fourteen days would be assessed against stream standards.

The technical work done by other states has been an important resource during our own process of developing criteria. The work has proven especially useful for perspective where similar uses are being protected. For example, chlorophyll criteria have proposed or adopted for cold-water aquatic life by five other states. Because, states have different protocols for assessing criteria, values were adjusted to a common basis for comparison to Colorado proposals. After adjustment to a common basis, the Division's proposal is 6 ug/L, compared to thresholds of 4 to 11 ug/L for the other states. The range is relatively narrow, and the Division's proposal is in the middle.

The comparison is more complicated for Warm lakes because of the wide variety of fish species that may be managed in a warm water fishery. After adjustment to a common basis, the Division's proposal is 15 ug/L, compared to thresholds of 9 to 37 ug/L for other states. An alternative comparison is limited to the only other standard specifically established for cool water fisheries. The adjusted chlorophyll criterion for Virginia's cool water fisheries is 15 ug/L, which is quite close to the Division's proposal.

11. Glossary

304a criteria: EPA recommendations for ambient water quality criteria. Established as required by the Clean Water Act and intended as guidance for States.

Algae: Small, generally microscopic, organisms inhabiting lakes and streams. There are many species from taxonomically diverse groups. Most of the groups are plants, but there is one prominent group of bacteria – Cyanobacteria (also referred to as blue-green "algae"). Algae inhabiting the open water of lakes are called phytoplankton. The ability to photosynthesize supplies energy at the base of aquatic food webs and produces oxygen that is released into the water.

Anoxic: Absence of dissolved oxygen; often a characteristic of the *hypolimnion* in *eutrophic* lakes.

Bloom: Usually refers to excessive algal abundance that may happen quickly. In this document, bloom refers specifically to chlorophyll concentrations in excess of a specific threshold (30 ug/L).

Centrarchids: Fish of the family Centrarchidae, which includes important game fish like largemouth bass and crappie.

Chlorophyll: The primary "pigment" that all algae use for photosynthesis is chlorophyll *a*. It is found within the algal cells and is responsible for the green color of algae. Frequently measured as an indicator of algal abundance.

Cyanobacteria: see *Algae*

Cyanotoxin: A toxin produced by one or more species of Cyanobacteria. There are many toxins and different modes of action. *Microcystin* is a relatively common cyanotoxin.

Disinfection by-product: A class of chemicals formed when water is treated with a disinfectant (e.g., chlorine). Two common categories formed when the disinfectant reacts with natural organic matter are trihalomethanes and haloacetic acids, both of which are regulated because they pose a risk to human health.

Ecoregions: A tiered system of large geographic regions with similar ecological systems. The contiguous states contain 10 Level-1 ecoregions, three of which are represented in Colorado.

Epilimnion: The uppermost layer of a stratified lake. This layer is mixed by the wind and is usually the region where photosynthesis occurs and algal biomass accumulates. See also *stratification*.

Eutrophic: see *Trophic state*

Eutrophication: A process of increasing the productivity of a lake by enriching the nutrient supply. The opposite of *oligotrophication*. When nutrient enrichment is the result of human actions, as is most often the case, the process may be called cultural eutrophication.

Geosmin: A chemical compound that is produced chiefly by *algae* and that is a major cause for complaints about taste-and-odor in treated drinking water.

Hydraulic residence time: A measure of how long, on average, water remains in a lake. It is calculated as the lake volume (acre-feet) divided by the outflow rate (acre-feet per year) and has units of years.

Hypolimnion: The bottom layer of a stratified lake. Because this layer has no gas exchange with the atmosphere, it is often a region in which dissolved oxygen is depleted. See also *stratification*.

Limnology: The scientific study of lakes, including physics, chemistry, and biology. (Freshwater equivalent of oceanography).

Load: The rate of delivery at which a pollutant is delivered to a lake. It may be expressed as mass per unit time (e.g., pounds per year) or mass per unit area per unit time (e.g., $mg/m^2/day$).

Lognormal: A statistical distribution that is frequently appropriate for water quality variables. Chlorophyll concentration data, for example, often conform to a lognormal distribution because there will be a few high values along with a larger group of comparatively small values (i.e., the distribution is "skewed" to the right). Log transformation of the concentration values results in a symmetrical (bell-shaped) normal distribution.

Mesotrophic: see *Trophic state*

Microcystin: A common *cyanotoxin* produced by a number of species of *Cyanobacteria*. The toxin affects the liver (hepatotoxin).

Oligotrophic: see *Trophic state*

Oligotrophication: A process of reducing the productivity of a lake by controlling the nutrient supply. The opposite of *eutrophication*.

Paleolimnology: A sub-discipline of *limnology* that reconstructs environmental history based on analysis of lake sediments.

Photosynthesis: The process by which algae convert solar energy into carbohydrates.

Phytoplankton: *Algae* that are freely suspended in the water column of lakes and transported almost entirely by water currents.

Reference condition

Salmonids: Fish of the family Salmonidae, which includes important game fish like trout and salmon.

Secchi depth: A measure of transparency or clarity of lake water. A Secchi disk, which is an 8-inch disk with alternating white and black quadrants, is lowered until it just disappears from view.

Stratification: The process by which lakes form layers based on differences in density. Typically refers to thermal stratification where the density gradient arises from temperature differences. The warmest layer – *epilimnion* – is on top, and the coolest layer – *hypolimnion* – is on the bottom. Thos two layers are separated by a region – metalimnion – with a strong temperature gradient.

Taxonomy: principles of scientific classification; a **taxon** is a fundamental unit of classification, like species (plural **taxa**).

Thermocline: The point within the metalimnion where the rate of change in temperature with depth is at its maximum for the water column. See *stratification*.

Trophic state: A classification of lakes based on increasing levels of productivity – oligotrophic, mesotrophic, eutrophic, and hyper-eutrophic – usually assessed in terms of algal abundance (chlorophyll concentration), but with corresponding boundaries for nutrients and transparency.

Zooplankton: Microscopic animals that are freely suspended in the water column of lakes. Feed on *algae* and are fed upon by fish.

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